National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Alaskan National Park Glaciers - Status and Trends

Second Progress Report

Natural Resource Data Series NPS/AKR/NRDS—2012/404

ON THE COVER

Knife Creek Glacier in June 2011. The tephra-covered ablation zone of the “fourth” glacier is visible in the middle distance, while in the right foreground a moat is visible where the “first” glacier has retreated from well-bedded pyroclastic material deposited during the 1912 Novarupta eruption. Katmai National Park and Preserve.

Photograph by: JT Thomas

Alaskan National Park Glaciers: Status and Trends

Second Progress Report

Natural Resource Data Series NPS/AKR/NRDS—2012/404

Anthony Arendt, Chris Larsen

Geophysical Institute
University of Alaska Fairbanks
903 Koyukuk Drive
Fairbanks, AK 99775

Michael Loso

Environmental Science Dept
Alaska Pacific University
4101 University Drive
Anchorage, AK 99508

Nate Murphy, Justin Rich

Geophysical Institute
University of Alaska Fairbanks
903 Koyukuk Drive
Fairbanks, AK 99775

October 2012

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Please cite this publication as:

Arendt, A., C. Larsen, M. Loso, N. Murphy, and J. Rich. 2012. Alaskan National Park glaciers - status and trends: Second progress report. Natural Resource Data Series NPS/AKR/NRDS—2012/404. National Park Service, Fort Collins, Colorado.

NPS 953/117460, October 2012

Contents

Contents (continued)

Page

Figures

Page

Figures (continued)

Page

Figures (continued)

Page

Tables

Executive Summary

This is the second progress for a multi-year study of glaciers in Alaskan national parks. The project will be completed in December 2013. Here we present results from mapping of all glacier extents in Katmai National Park and Preserve (NP&P) and Lake Clark NP&P and from measurements of surface elevation changes on select glaciers in Lake Clark NP&P. We also summarize field efforts to date associated with the focus glacier component of the project and present a sample focus glacier vignette. We have accomplished all tasks on schedule for this second deliverable, and we look forward to continued conversation with our colleagues at NPS as the project moves forward. Significant results include the following:

- Katmai NP&P was 5.2% glaciated in the early period (nominally 1956), but ice cover diminished 15% by the modern period (2009), to become 4.4% glaciated (911 km^2).
- Lake Clark NP&P was 22.2% glaciated in 1956, but ice cover diminished 11% by the modern period, to become 19.7% glaciated (3233 km^2).
- The vast majority of glaciers in both parks have shrunk considerably, mainly by terminus retreat, in that time. The total number of glaciers, in contrast, has grown in both parks. This may be partly an artifact of differing map/imagery quality, but it largely reflects the breakup of large glaciers into multiple smaller ice masses.
- In Katmai NP&P, a significant minority of glacier termini in the Kejulik Mountains advanced after 1956. We attribute most of these advances to lingering effects (primarily reduced ablation) of ash deposition from the 1912 Novarupta eruption.
- Only one significant terminus advance occurred in Lake Clark NP&P since 1956, on the south side of Redoubt Volcano. Around and south of Little Lake Clark, several small glaciers that grew significantly or “appeared” since 1956 may reflect cartography errors in the original maps.
- Using laser altimetry, we measured 14 distinct intervals of elevation change distributed among eight glaciers in Lake Clark NP&P from 1996 - 2001 and/or 2001 - 2008. During the earlier interval, all but one glacier (Turquoise) had slightly positive glacier-wide mass balance rates (overall thickening). In the later interval, every glacier had negative rates (overall thinning).
- The lowest measured balance rate (greatest thinning) was on Tlikakila North Glacier from 2001-2008: ice loss averaged 1.40 m/yr over the entire glacier surface.
- We visited eleven and photographed two other focus glaciers in summer 2011. Resources sufficient for construction of vignettes are now available for all focus glaciers except the Aniakchak Caldera Icefields, Fourpeaked Glacier, and Turquoise Glacier.
- A sample vignette for the Knife Creek Glacier has now been vetted by NPS personnel and project collaborators, and will serve as the model as we commence planning for the layout and design phase for the final report.

Acknowledgments

We acknowledge the advice and contributions of our NPS collaborators Bruce Giffen, Guy Adema, Fritz Klasner, Rob Burrows, and Denny Capps. Support for focus glacier work at Katmai and Lake Clark was kindly provided by Rich and Megan Richotte, Page Spencer, Chuck Lindsay, Whitney Rapp, Jeff Shearer, and Angela Olson. Finally, we thank all the many scientists whose work has helped build the foundation upon which this project is built.

Introduction

Project Overview

Basic information on the extent of glaciers and how they are responding to climatic changes in Alaska NPS units is lacking. Because glaciers are a central component of the visitor experience for many Alaskan parks, because the complicated relationship between glaciers, humans, and the climate system constitutes a significant interpretive challenge for NPS staff, and because glacier changes affect hydrology, wildlife, vegetation, and infrastructure, this project was initiated to document the status and recent trends in extent of glaciers throughout the nine glaciated park units in Alaska. The work will also be of substantial interest to scientists who recognize recent changes in Alaskan glaciers, including their collective contribution to sea level rise, as both globally significant and under-studied.

Of Alaska's 15 national parks, preserves, and monuments, nine contain or adjoin glaciers: Aniakchak (ANIA), Denali (DENA), Gates of the Arctic (GAAR), Glacier Bay (GLBA), Katmai (KATM), Kenai Fjords (KEFJ), Klondike Gold Rush (KLGO), Lake Clark (LACL), and Wrangell-St. Elias (WRST). Under this project, status and trends of glaciers within (or in isolated cases—adjacent to) these park units will be assessed in three primary ways: changes in extent (area) for all glaciers, changes in glacier volume for all glaciers with available laser altimetry, and an interpretive-style description of glacier and landscape change for 1-3 "focus glaciers" per park unit. These components of the project, summarized in Table 1, are described in more detail in the methods section of this report.

Table 1. Overall scope of project by component: PI, glacier coverage, and types of analyses.

	Extent Mapping	Volume Change	Focus Glaciers
Principal Investigator	Dr. Anthony Arendt	Dr. Chris Larsen	Dr. Michael Loso
Affiliation	Geophysical Institute, University of Alaska Fairbanks	Geophysical Institute, University of Alaska Fairbanks	Environmental Science Dept, Alaska Pacific University
Contact	arendta@gi.uaf.edu	chris.larsen@gi.uaf.edu	mloso@alaskapacific.edu
Analyses	Map modern and historic outlines of glaciers from topo maps and satellite imagery	Determine glacier surface elevation changes over time with repeat laser altimetry	Graphic/narrative summary of glacier response to climate and landscape-scale impacts
Glacier Coverage	All glaciers in all units, some park-adjacent glaciers	Existing coverage: ~1000 total flightlines in parks	1-3 per park unit

Project Deliverables and Timeline

The results of our work will be presented in two written products: a technical report and an interpretive report. Dr. Loso has primary responsibility for the content of both publications – NPS will provide layout and production.

The *technical report*, published internally as a Natural Resource Technical Report, will be a comprehensive technical document prepared to thoroughly document the data sources, methodology, and results of the project, to analyze those results, and to discuss the implications of those analyses. The technical report will be accompanied by a permanent electronic archive of geographic and statistical data and is intended to serve a specialized audience interested in working directly with the project's datasets. It will therefore be complete, lengthy, and cumbersome to read for scientists interested primarily in the project's findings and implications. Those audiences will find a comprehensive, but more accessible, discussion of the project's results and implications in the interpretive report, discussed below.

The *interpretive report* will be a non-technical document suitable for glaciologists, park interpretation specialists, park managers, and park visitors with no particular background in science or glaciology. The document will be comprehensive and thorough, however, and is envisioned as graphics and photo-intensive, content rich, and accessibly written. Content will be prepared to fit in a publication similar to an existing model: [Winkler GR. 2000. *A Geologic Guide to Wrangell-St. Elias National Park and Preserve, Alaska*. USGS Professional Paper 1616, 166 pp.] Content will include a comprehensive literature review, and also detailed—but accessible—summaries of the key data sources, methodologies, and findings of the technical report. We will utilize the "focus glaciers" as a primary narrative tool to describe status and trends in NPS glaciers.

Separately from these primary publications, the principal investigators—in collaboration with other research associates and NPS staff, as appropriate and willing—will publish the research results of most broad and compelling scientific interest in a more concise form in one or more peer-reviewed journals (e.g. *Journal of Glaciology*). These articles are not considered project deliverables. Interpretive summaries may also be produced based on region-wide and/or park-by-park themes. These 2 page (front and back) summaries, published internally by NPS, would summarize the most broad and compelling findings of scientific interest.

The project was initiated with a kickoff meeting held October 11, 2010 and is scheduled for completion December 15, 2013. Interim project tasks and deliverables are summarized in Table 2, and are subject to modification in each year's annual meeting and task agreement.

Scope of Progress Report 2

This is the second of four progress reports due biannually during the first two years of the project (Table 2). These reports are meant to be technical in nature and park-centered. They may contain some analysis on parks with completed data products, and in other cases may simply present data products that remain incomplete. Parks scheduled for presentation in this report are Katmai and Lake Clark (extent mapping and volume change only, noting that no volume change data exists for Katmai at this time). We also present a simple summary of field efforts associated with the focus glacier component, and include a sample glacier vignette previously presented at the SWAN Park Science Meeting in November 2011.

Table 2. Schedule for project tasks and deliverables. Report is under the direction of Loso, but relies substantially on timely contribution by all collaborators.

Date	Extent Mapping-Arendt	Volume Change-Larsen	Focus Glaciers-Loso	Reporting-Loso et al.
9/30/11	Glacier Bay, Denali	Glacier Bay	Glacier Bay	Progress Report 1
3/30/12	Katmai, Lake Clark	Katmai, Lake Clark	Summary of field efforts*	Progress Report 2
9/30/12	Gates of the Arctic, Klondike, Aniakchak	Denali	Katmai, Lake Clark, Denali	Progress Report 3
3/30/13	Kenai Fjords, Wrangell-St. Elias	Kenai Fjords, Wrangell-St. Elias	Summary of field efforts*	Progress Report 4
5/31/13	Remaining data and analyses	Remaining data and analyses	Remaining data and analyses	Progress Report 5
9/30/13			Report prep	Draft Final Report
11/1/13	Report review	Report review		
12/15/13			Report prep	Final Report

* only as dictated by actual fieldwork

Because it was our first substantive written communication to the project sponsors, the first progress report placed considerable emphasis on defining the project and our approach to it. In this second and subsequent progress reports, we will focus our efforts on presentation of data products. Much of the text in the *introduction* and *methods* is appropriated from the previous report and has only minor changes.

Study Areas

Alaska is the largest and most heavily glaciated of the fifty United States. With an area of 1,530,693 km^2, approximately 75,000 km^2, or ~5% of the land area, are covered by glacial ice (Post and Meier, 1980). The number of glaciers in the state is not precisely known, but probably exceeds 100,000 (Molnia, 2001). Approximately 18,500 km^2 of the state's glaciers (~25%) are on lands administered by the National Park Service. Statewide, NPS administers 15 national parks, preserves, monuments, and national historical parks; glaciers occur in (or adjacent to, in the case of Klondike Gold Rush) 9 of those units:

- Aniakchak National Monument and Preserve
- Denali National Park & Preserve
- Gates of the Arctic National Park & Preserve
- Glacier Bay National Park & Preserve
- Katmai National Park & Preserve
- Kenai Fjords National Park
- Klondike Gold Rush National Historic Park
- Lake Clark National Park & Preserve
- Wrangell-St. Elias National Park & Preserve

This progress report focuses on two of those units: Katmai (Figure 1) and Lake Clark (Figure 2). We describe these in more detail below. Subsequent progress reports, and the final report, will address glacier status and trends in the other remaining units.

Katmai National Park and Preserve

Katmai National Park and Preserve was established in 1918 (as Katmai National Monument) to preserve the spectacular and dynamic landscape associated with the 1912 eruption of Novarupta Volcano—the world's largest volcanic eruption of the 20th century. The Valley of Ten Thousand Smokes was and is a central attraction of the Park, but Katmai is now equally famous for its populations of brown bears and fish. The Park encompasses ~20,610 km^2 of federal land. Located on the Alaska Peninsula between Cook Inlet and Bristol Bay, the Park's mountains are relatively low and reach their greatest heights on the eastern edge of the Park where the Aleutian Range crests at 7606' (2318 m) on Mount Denison. Near park headquarters in King Salmon, average January low temperature is -13° C and average July high is 17° C. Annual precipitation is 48 cm.

Katmai NP&P (including glaciers wholly or partly inside of the Park boundary) has an ice-covered area of around 911 km^2 based on satellite imagery mostly from 2009. Glaciers are clustered in 3 groups: on the Kejulik Mountains to the south, on Fourpeaked Volcano in the east, and scattered in the Walatka Mountains in the north. Collectively, the glaciers range from 58˚06' N to 58˚59' N and spans from 153 27' W to 155˚27' W. Glaciers in the Park are mostly modestly-sized and land-terminating, and stand out in a regional sense mostly for their response to extensive deposition of volcanic ash, especially after the massive 1912 Novarupta eruption.

Lake Clark National Park and Preserve

Lake Clark National Park & Preserve is located in western Alaska, southwest of—and across Cook Inlet from—Anchorage. The Park was first established in 1980 to protect scenic beauty (including volcanoes, glaciers, wild rivers, and waterfalls), populations of fish and wildlife, watersheds essential for red salmon, and the traditional lifestyle of local residents. It contains ~16,390 km^2 of federal land. Along with its signature feature, 66 km long Lake Clark, the Park features three active volcanoes (Spurr, Redoubt, and Iliamna) and the intersection of two major mountain ranges: the Aleutian and Alaska Ranges. Climate is quite variable; elevations range from sea level on the Cook Inlet coast to over 11,000' (3350 m) on Mt. Spurr. Near park headquarters in Port Alsworth, average January low temperature is -15° C and average July high is 20° C. Annual precipitation is 36 cm.

Lake Clark's glaciers (including glaciers wholly or partly inside of the Park boundary) covered around 3233 km^2 as of 2009. Glaciers are scattered throughout the central and eastern portion of the park, originating on two volcanoes (Iliamna and Redoubt) and three mountain ranges (the Chigmit and Neacola Mountains and the southernmost extension of the Alaska Range). In the northeastern part of the park, glaciers of the Neacola Mountains are contiguous with additional ice outside the park boundary that add a substantial amount to the glacier areas measured in this park. Indeed, the two largest glaciers in this inventory, Tanaina Glacier and Blockade Glacier, originate outside the park boundary. The largest glacier contained mostly within the Park boundary is Double Glacier, with an area for the main ice mass of over 137 km^2. Within the Park proper, glaciers range from 59˚52' N to 61˚31' N and from 152˚12' W to 154˚04' W. None of the Park's glaciers reach tidewater.

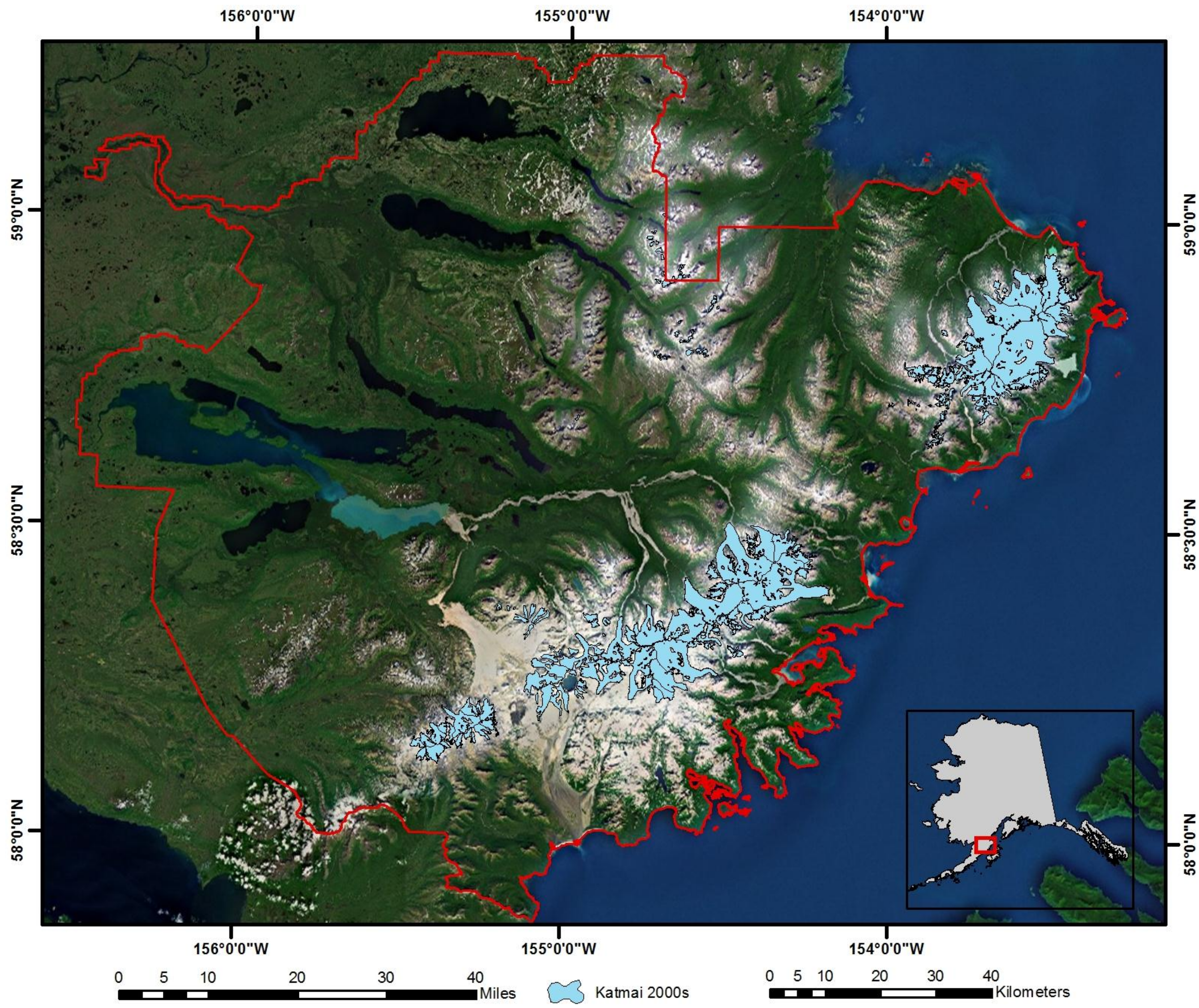


Figure 1 Katmai National Park and Preserve. Blue polygons are current ice coverage, red lines are park outlines.

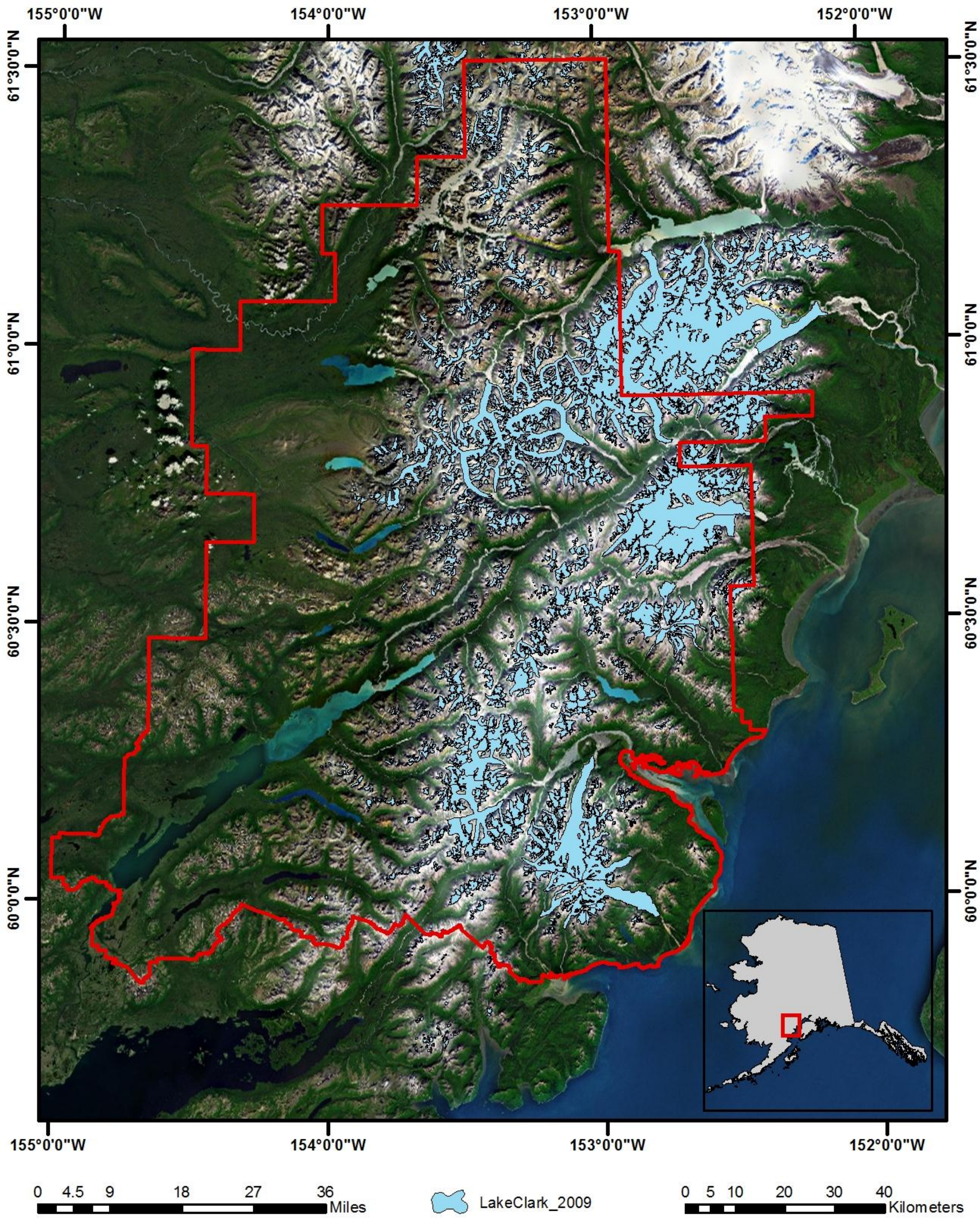


Figure 2. Lake Clark National Park and Preserve). Blue polygons are current ice coverage, red lines are park outlines.

Methods-Mapping

Data

The mapping component of this project aims to delineate the outlines of all glaciers in all Alaskan parks for two time intervals: mid-20th century (based mainly upon USGS topographic mapping from that time period; median map date is 1956) and the early 2000s (based upon latest available satellite imagery; 2009 is typical). For simplicity, we subsequently refer to these time intervals as "map date" (nominally 1956) and "modern" (2009). Topographic map coverage is based on photography that dates back as early as 1949 and as late as 1957, with some later revisions. Post-2000 (mostly 2008-2010) satellite data for this phase of the project are from a combination of Landsat and Ikonos imagery. Detailed source information for mapping presented in this report is presented in Table 3. Note that some modern mapping in Lake Clark was done using an Ikonos image mosaic with tiles that at present are not clearly identified by scene or date. We believe most of the images in the mosaic are 2004-2010, and will resolve this ambiguity before the final report.

Analysis

PI Anthony Arendt and research technician Justin Rich have developed a standardized workflow for the generation and distribution of glacier shapefiles and associated geostatistics for these glaciers (Figure 3). We have automated the procedure whenever possible to minimize errors, and to provide for future outline generation after this project is complete. Justin Rich has developed algorithms that provide for automatic delineation of glacier boundaries from multispectral satellite imagery, and has also produced an algorithm to improve the usability of post-2003 Landsat imagery that is corrupted by scan line correction (SLC) errors.

Figure 3. Workflow for the generation of glacier inventory data for NPS glaciers. Note that we are revising our approach to sharing data with GLIMS and GINA (at right in this figure).

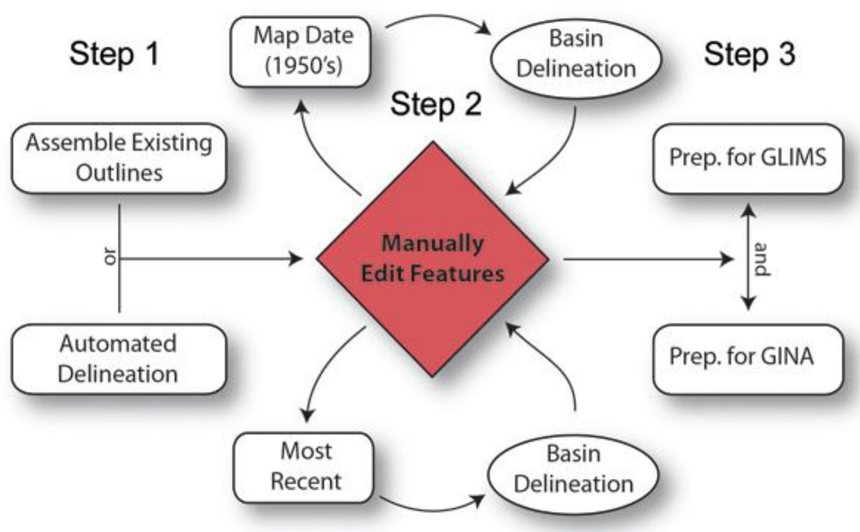


Table 3. Data sources for mapping. Above: sources for modern satellite imagery. Dates and scene numbers not currently available for some Ikonos mosaics used. Below: historic maps. All are USGS 1:63000 quadrangles in NAD1927 with units feet.

Park	FileID	Date	Long (center)	Lat (center)	Type
KATM	20090709_797_20002	7/9/09	-155.067598000000	58.632653000000	Ikonos
KATM	20080725_295_10000	7/25/08	-155.166014000000	58.261248000000	Ikonos
KATM	20090709_797_20004	7/9/09	-153.822664000000	58.630716000000	Ikonos
KATM	20090711_697_50000	7/11/09	-154.739823000000	58.243342000000	Ikonos
KATM	20090711_697_50001	7/11/09	-154.306983000000	58.246666000000	Ikonos
KATM	20090711_698_40000	7/11/09	-154.731836000000	58.328901000000	Ikonos
KATM	20090711_698_40001	7/11/09	-154.270669000000	58.330067000000	Ikonos
KATM	20090824_723_00000	8/24/09	-154.754687000000	58.439386000000	Ikonos
KATM	20090824_723_00001	8/24/09	-154.155211000000	58.449617000000	Ikonos
KATM	20090904_505_20001	9/4/09	-155.365765000000	58.162136000000	Ikonos
KATM	20090904_505_20002	9/4/09	-154.857909000000	58.162513000000	Ikonos
KATM	20090619_528_00000	6/19/09	-154.726381000000	58.375651000000	Ikonos
KATM	20090926_741_10000	9/26/09	-154.800570000000	59.028076000000	Ikonos
KATM	20090619_528_00001	6/19/09	-154.205254000000	58.379587000000	Ikonos
KATM	20090619_529_00000	6/19/09	-154.295895000000	58.973476000000	Ikonos
KATM	20090619_529_00001	6/19/09	-153.701288000000	58.972998000000	Ikonos
KATM	20090706_065_10002	7/6/09	-154.766280000000	58.889813000000	Ikonos
LACL	LE70700172010256EDC00	9/13/10	-151.641050000000	61.473610000000	LANDSAT ETM+
LACL	LE70720172010270EDC00	9/27/10	-154.740510000000	61.474310000000	LANDSAT ETM+
LACL	LE70700182009189EDC00	7/8/09	-152.604550000000	60.088840000000	LANDSAT ETM+

Park	FileID	Pub Year	Photo Year	Revisions
KATM	MT KATMAI C-2	1953	1951	1966
KATM	MT KATMAI D-3	1951	1951	1972
KATM	MT KATMAI C-3	1951	1951	1981
KATM	AFOGNAK D-5	1951	1951	1987
KATM	MT KATMAI A-2	1951	1951	1994
KATM	MT KATMAI B-2	1951	1951	1991
KATM	MT KATMAI A-5	1951	1951	1984
KATM	MT KATMAI B-4	1951	1951	1973
KATM	MT KATMAI B-3	1951	1951	1970
KATM	AFOGNAK C-5	1951	1951	1973
KATM	MT KATMAI D-2	1951	1951	1973
KATM	AFOGNAK D-6	1951	1951	1983
KATM	MT KATMAI D-1	1953	1951	1967
KATM	MT KATMAI B-1	1951	1951	1977
KATM	MT KATMAI A-4	1951	1951	1984
KATM	AFOGNAK C-6	1951	1951	1973
KATM	MT KATMAI A-3	1951	1951	1977
KATM	MT KATMAI C-1	1951	1951	1973
LACL	TYONEK D-5	1954	1953	1972
LACL	TYONEK B-7	1958	1956	1975
LACL	ILIAMNA D-2	1958	1957	1977
LACL	LAKE CLARK B-1	1958	1957	
LACL	TYONEK B-5	1958	1952	1970
LACL	TYONEK A-7	1958	1956	1979
LACL	TYONEK B-6	1958	1953	1974
LACL	TYONEK C-5	1954	1953	1971
LACL	LIME HILLS D-4	1958	1956	1975
LACL	LAKE CLARK B-3	1954	1957	1980
LACL	TALKEETNA A-6	1958	1957	1973
LACL	MCGRATH A-3	1958	1955	
LACL	LAKE CLARK C-2	1958	1957	1970
LACL	MCGRATH A-1	1958	1957	
LACL	LIME HILLS D-1	1958	1956	
LACL	LIME HILLS B-1	1958	1956	1977
LACL	TYONEK D-8	1958	1957	
LACL	LAKE CLARK D-2	1958	1957	1969
LACL	LAKE CLARK A-3	1954	1957	1970
LACL	TYONEK D-7	1958	1957	1973
LACL	LAKE CLARK D-3	1954	1957	
LACL	LIME HILLS A-1	1958	1956	
LACL	LIME HILLS D-2	1958	1956	1977
LACL	KENAI C-7	1958	1956	1972
LACL	TYONEK C-8	1958	1955	
LACL	MCGRATH A-2	1958	1954	
LACL	KENAI D-7	1958	1956	
LACL	LAKE CLARK B-2	1958	1957	1971
LACL	KENAI C-8	1958	1956	1979
LACL	LIME HILLS C-4	1958	1956	
LACL	LIME HILLS B-4	1954	1957	
LACL	LAKE CLARK A-2	1958	1957	1970
LACL	KENAI B-7	1958	1954	1973
LACL	LIME HILLS A-2	1958	1956	
LACL	KENAI A-8	1958	1956	
LACL	ILIAMNA D-1	1958	1957	1982
LACL	LIME HILLS C-2	1958	1956	1975
LACL	TYONEK A-6	1958	1955	1985
LACL	LIME HILLS C-1	1958	1955	
LACL	TYONEK C-6	1958	1955	1973
LACL	LIME HILLS D-3	1958	1956	1975
LACL	LAKE CLARK C-1	1958	1957	
LACL	TYONEK D-6	1958	1955	1971
LACL	TYONEK A-8	1958	1956	
LACL	LAKE CLARK A-1	1958	1957	
LACL	SELDOVIA D-8	1958	1956	1991
LACL	LAKE CLARK C-3	1954	1957	
LACL	KENAI B-8	1958	1956	
LACL	KENAI D-6	1958	1954	1973
LACL	LIME HILLS B-3	1954	1957	
LACL	LAKE CLARK D-1	1958	1957	
LACL	LIME HILLS B-2	1958	1956	1970
LACL	TYONEK C-7	1958	1955	
LACL	ILIAMNA C-2	1958	1955	1972
LACL	KENAI D-8	1958	1956	1988
LACL	LIME HILLS C-3	1958	1949	
LACL	TYONEK B-8	1958	1957	1985
LACL	TALKEETNA A-5	1958	1957	1975

Details of the workflow shown in figure 3 are described below, and the steps are shown by example in Figure 4.

Step 1: Existing outlines are assembled if they exist. These may come from previous UAF altimetry work, NPS scientists, or from other colleagues working on these areas. Otherwise, an automated delineation algorithm is run using multispectral satellite imagery to produce a first estimate of glacier extent.

Step 2: We perform heads-up (on-screen) manual digitization on the computer to clean up existing outlines so that they more accurately match map or satellite imagery. Editing is performed at a scale appropriate to the base imagery: between 1:10,000 and 1:20,000 for Landsat imagery, and between 1:1500 and 1:5000 for Ikonos imagery. Once the product is of suitable quality, we run it through a basin delineation algorithm written by UAF PhD student Christian Kienholz. We perform additional manual digitization, primarily to ensure the automatically produced basins match what we would expect in reality. We then populate the attribute table with glacier names (where available), calculate glacier areas, and use a standard code to describe anomalous glacier types where this information is known: e.g. surge-type, tidewater, etc. (Paul et al. 2009).

Step 3: We run a final series of scripts that set up the files for ingest into a standard data distribution format. As part of this step we write metadata files that describe what imagery was used, what dates are covered, and other information. At present, the product exported from these final scripts includes:

- Glacier ID
- Name (if available)
- Date of imagery used
- Centroid latitude and longitude
- Glacier area (km^2)
- Min, max, and area-weighted mean/median glacier elevations (m)
- Hypsometry data, presented as glacier areas within 50 m elevation bins

Work is ongoing to more robustly calculate glacier slope and aspect, and these fields will be included in the final product. Detailed field definitions are provided in Appendix C.

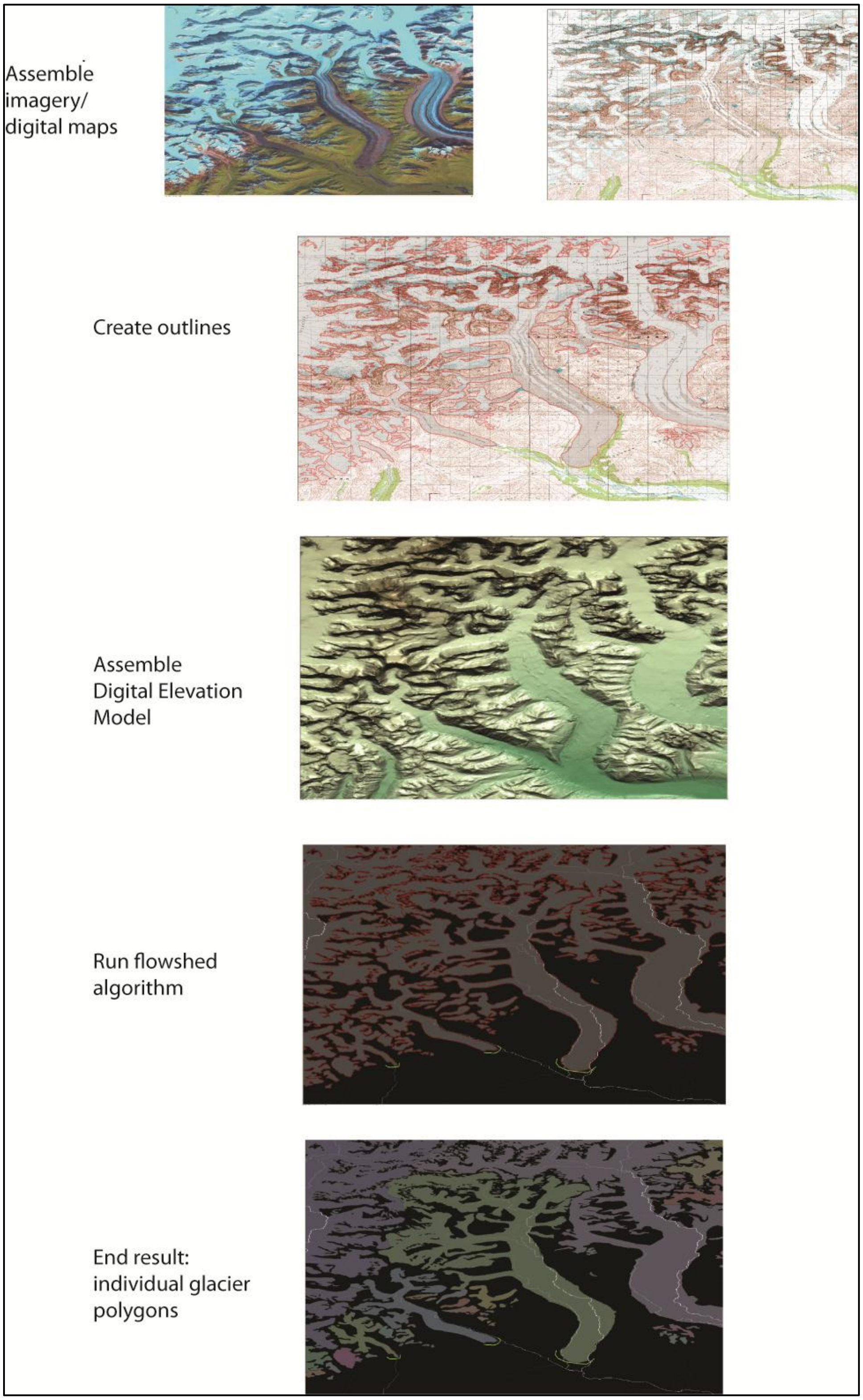


Figure 4. Imagery (from Tokositna and Ruth Glaciers, Denali NP&P) demonstrating generation of glacier inventory data for NPS glaciers.

Methods-Elevation Change

The elevation change component of this project aims to characterize changes in surface elevations of all glaciers (within glaciated Alaskan parks) that have existing laser point data from two or more time intervals since this work commenced in the mid-1990s. No new laser altimetry data will be acquired under the scope of this project. Existing laser altimetry profiles (as of January 2011) for Lake Clark are shown in Figure 5 and Table 4. Seven other glaciers in Lake Clark NP&P, and one glacier in Katmai NP&P, were profiled in 2008 but have not been repeated.

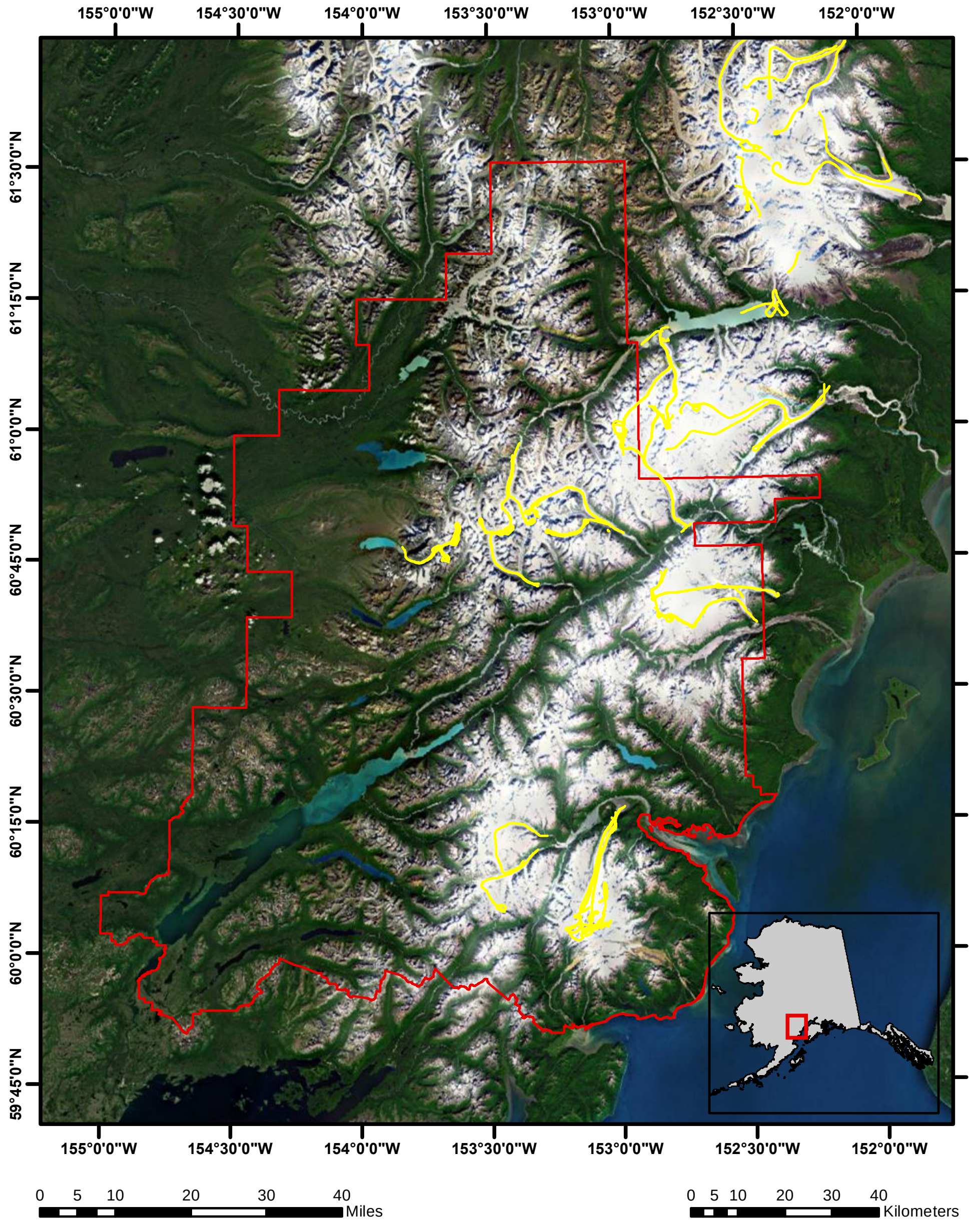


Figure 5. Existing laser altimetry profiles (yellow lines) in Lake Clark National Park and Preserve (red polygon) as of January 2011.

Table 4. Date of laser altimetry flights for glaciers located in Lake Clark Park and Preserve. All profiles were acquired during the last week of May and the first week of June. Glacier types are land terminating (L), lake calving (LK), and surge (S). Glaciers for which only one profile observation exists are not shown.

Double North (LK)	Double South (L)	Shamrock (LK)	Tanaina (L)	Tlikakila Glacier Fk (L)	Tlikakila North Fk (L)	Turquoise (L)	Tuxedni (S)
5/14/96	5/14/96	5/14/96	5/14/96	5/13/01	5/13/01	5/16/96	5/13/96
5/13/01	5/13/01	5/13/01	5/13/01	5/21/08	5/21/08	5/13/01	5/13/01
5/26/08	5/26/08	5/21/08	5/21/08			5/26/08	5/26/08

Data
Elevation change estimates are based upon laser point data acquired from aircraft at discrete time intervals. Laser point data has been acquired with three different systems since data collection began in 1995, including two different laser profilers before 2009 and a scanning laser system since then. The laser profilers have been described in previous publications (Arendt et al. 2002; Echelmeyer et al. 1996; Sapiano et al. 1998). The data acquired during those earlier missions have been reprocessed with the same methods as post-2009 data, which was acquired with a Riegl LMS-Q240i that has a sampling rate of 10,000 points per second, an angular range of 60 degrees, and a wavelength of 900 nm. The average spacing of laser returns both along and perpendicular to the flight path at an optimal height above glacier of 500 m is approximately 1 m x 1 m with a swath width of 500 – 600 m. The aircraft is oriented using an inertial navigation system (INS) and global position system (GPS) unit. The INS is an Oxford Technical Solutions Inertial+ unit that has a positioning accuracy of 2 cm, a velocity accuracy of 0.05 km/h RMS, and an update rate of 100 Hz. The GPS receiver is a Trimble R7 that records data at 5 Hz and has an accuracy of 1 cm horizontal and 2 cm vertical in ideal kinematic surveying conditions.

To translate laser point data to estimates of volume change, we require digital elevation models (DEMs) and glacier outlines for measured glaciers. The DEM is derived from the National Elevation Database (NED), a USGS product derived from diverse source data that generally (in Alaska) reflect elevations from the most recent topographic map at 2-arc-second (~60 m) grid spacing. Outlines and surface areas of each glacier are based upon “modern” glacier outlines developed elsewhere in this project.

Analysis
The workflow for calculation of elevation changes and derived volume changes follows these steps:

Step 1: Glacier surface elevations are derived from laser point data by integrating the GPS-based position of the aircraft on its flight path over a glacier, airplane orientation data from an onboard INS, and laser point return positions relative to the airplane. The combination of these data determines the position in 3-dimensional space of the laser point returns from the glacier surface. The points are referenced in ITRF00 and coordinates are projected to WGS84, with a coordinate accuracy in x, y, and z position of +/- 30 cm. Elevation data are recorded as height above ellipsoid.

Step 2: Glacier surface elevation profiles from different years can then be differenced to find the cumulative thickness change (dz, meters) over that time interval. Division by the time elapsed (dt, years) gives the rate of thickness change Δz (m/yr). This is determined with slightly different methods depending on whether data from the laser profiler (1995 – 2009) or laser scanner (2010 – 2011) are being used.

Step 3a: For laser profiler to laser profiler differencing, points that are located within 10 m of each other in the x-y plane are selected as common points between the different years. If more than one point is located within that 10 m grid, then the mode of the elevation is used for each grid point. These common points are then used in the determination of Δz. Since there are data points recorded only along the flight track at nadir with the laser profiler it is critical that these earlier flight paths were repeated as accurately as possible to obtain a large number of common points. Sometimes the flights were not repeated closely enough to provide extensive elevation change. This limits the robustness of the interpolated line that is fit to the data, especially if there is variability within the data.

Step 3b: For laser scanner to laser profiler differencing, a grid is made of the laser scanner swath at a resolution of 10 m. This grid is based upon the mode of all the points within each of the grid cells, which helps to filter out laser returns from crevasse bottoms. Then, the coordinates from each point in the old profile are used to extract an elevation from this grid (for all laser profiler points that fall within the new LiDAR swath extents). This laser scanner elevation is differenced with the laser profiler elevation at that point, giving the change in elevation. The same idea is used for laser scanner to laser scanner comparisons, but instead of using every point from the older laser scanner swath, an average value on a 10 m x 10 m is calculated out of the old swath, then the value for that point location is also extracted from the newer laser scanner grid.

Step 4: The complete series of Δz measurements at specific elevations along the glacier flight line is plotted as the median of a moving window of twelve data points from top to the bottom of the glacier. Plotted confidence intervals are based upon the interquartile range of the moving window. At both the lower and upper elevation limits of the glacier, Δz is forced to zero and the confidence interval is presented as an average of the interquartile ranges calculated along the entire profile.

Step 5: The NED-based DEM is used to develop an area-altitude distribution for the glacier in 30 m bins. Volume change is found by performing a numerical integration wherein the binned Δz line is multiplied by the binned AAD.

To facilitate comparison of volume changes among glaciers of different sizes, we convert volume changes to glacier-wide mass balance rates ($\dot{B}$), adhering to terminology in the Glossary of Mass Balance Terms (Cogley et al. 2011). The volume change is calculated assuming that the lost (or gained) volume was composed entirely of ice, e.g. Sorge's law (Bader, 1954). Volume change can then be converted to water equivalent (w.e.) by assuming a constant ice density of 900 kg/m3, and volume change presented as km3/yr. Glacier-wide mass balance rate is then just volume change divided by glacier surface area.

Methods-Focus Glaciers

The focus glacier component of this project aims to provide additional information about a small subset of glaciers in each glaciated Alaskan park for the purpose of demonstrating the potentially unique ways in which A) glaciers change in response to climate and other forcings, and B) landscapes respond to glacier change. The focus glacier portion of the final report will include a narrative description of each glacier and a collection of photos, maps, figures, and other graphical information. In comparison with the other components of this project, which are directed clearly towards generating and analyzing new or existing data, the focus glacier component is focused more on interpretation and synthesis. No new data will be acquired, but collection of existing materials is a central task for the PI Michael Loso. For each glacier, this collection of materials will ultimately be presented as a "vignette" in the final document. A sample vignette is presented in this progress report.

Focus Glacier Selection

The final list of focus glaciers is included below (Table 5) and mapped in Figure 6. The focus glaciers are not intended to be statistically representative of Alaskan glaciers as a whole, but rather were selected to collectively represent the diversity of glacier types and climatic responses evident statewide. Additional supporting criteria for inclusion in the list were a rich history of visitation/ documentation and public accessibility. Since October 2010, the list evolved some under the advice and guidance of NPS staff, particularly including NPS unit resource staff and regional I&M staff. No changes have occurred since the First Progress Report.

Summary of Field Efforts

In summer 2011, PI Loso visited several NPS units to collect existing resource materials and develop first-hand familiarity with some of the focus glaciers. The objectives were to develop a first-hand familiarity with the field site geography, collect photographs (including, in some cases, repeat photographs of historic imagery), interview researchers and NPS staff working on or near each glacier, and qualitatively document the diverse evidence of landscape change.

The diverse historic and contemporary reference materials necessary for development of the focus glacier vignettes cannot be found solely through traditional library and internet resources; many resources are available only from NPS/NPS-affiliated personnel at AKRO and at the individual parks. Examples of collected materials include:

- Published, peer-reviewed journal articles
- Internal NPS (and occasionally other agency) reports
- Internal NPS unpublished data, when available
- Historic maps
- Satellite and aerial imagery
- Interviews with knowledgeable persons
- Original and historic photography

Table 5. Focus glaciers for each of Alaska's 9 glaciated park units. "Snapshot" briefly denotes unique aspects of each glacier. PI Loso has personal knowledge of "visited" glaciers. Glaciers with a "poor" historic record may require additional work, outside the original scope, if they are to be included in the final report.

Park	Glacier(s)	Snapshot	Visited	Historic record
ANIA	Caldera icefields	Only permanent ice in Aniakchak. Virtually unstudied. Tiny.	no	poor
DENA	Kahiltna Glacier	Popular climbing and flightsee route. Non-surging valley glacier.	yes	good
	Muldrow Glacier	Backcountry accessible surge-type valley glacier.	yes	good
	Toklat Glacier	Backcountry accessible cirque glacier with history of NPS study.	no	good
GAAR	Arrigetch glaciers	High visitation for a remote park. Small, arctic cirque glaciers.	yes	good
GLBA	Brady Glacier	Remote tidewater glacier with very low-elev accumulation zone.	yes	good
	Margerie Glacier	Cruise-ship visible, tidewater. High-elev accumulation zone.	yes	good
	Muir Glacier	Formerly tidewater glacier with spectacular retreat history.	yes	excellent
KATM	Fourpeaked Glacier	Valley glacier on an active volcano. Remote.	no	poor
	Knife Creek Glaciers	Unusual tephra-covered glacier with long historic record.	yes	good
KEFJ	Aialik Glacier	Tidewater glacier with historically stable terminus position.	no	moderate
	Exit Glacier	Tourist-popular, tidewater. On coastal side of Harding Icefield.	yes	excellent
	Skilak Glacier	Backcountry glacier draining interior side of Harding Icefield.	no	moderate
KLGO	Nourse Glacier	Outside park; moraine-dammed threatens infrastructure.	no	moderate
LACL	Tanaina Glacier	On flightseeing route at Lake Clark Pass. Changing hydroogy.	yes	moderate
	Turquoise Glacier	Cirque glacier with simple geometry. Remote.	no	good
	Tuxedni Glacier	Valley glacier on an active volcano. Remote.	yes	moderate
WRST	Bagley Icefield	Huge icefield with multiple distributaries. Remote.	yes	good
	Kennicott Glacier	Highly visited, tourist-friendly valley glacier. Jokulhlaup history.	yes	excellent
	Yahtse Glacier	Tidewater glacier that is currently advancing.	yes	good

No materials were removed from any park except for photographs and paper/electronic copies of existing documents. All backcountry travel and camping was done using minimum impact techniques and there were no reportable incidents involving wildlife, or other park resources. Permits were obtained to allow field visits to any of the nine glaciated Alaskan parks. Of those nine, two were not visited. No work was carried out at Aniakchak or Klondike Gold Rush. These are not discussed further. Below, we provide dates and general descriptions of activities at each of the other 7 parks.

Denali: On June 6 and 7, 2011, Loso visited Kahiltna Glacier with professional photographer JT Thomas and also UAF collaborators Anthony Arendt and Joanna Young. Travel to the Eklutna was provided by NPS helicopter, which was used while en route to complete research work permitted separately by Arendt. We stayed one night at basecamp and in the morning completed additional fieldwork before returning to Talkeetna by fixed wing. Additional work may be completed in Denali at Toklat or Muldrow Glaciers in coming seasons.

Gates of the Arctic: Loso visited the Arrigetch Glacier region from August 2-12, 2011, accompanied by NPS ranger Tucker Chenoweth. Travel to and from the Arrigetch was via fixed wing travel from Fairbanks to Bettles and then into Circle Lake. We traveled on foot to the Arrigetch Valley, backcountry camping along the way, and photographed the glaciers there including repeat photographs of historic work by Tom Hamilton.

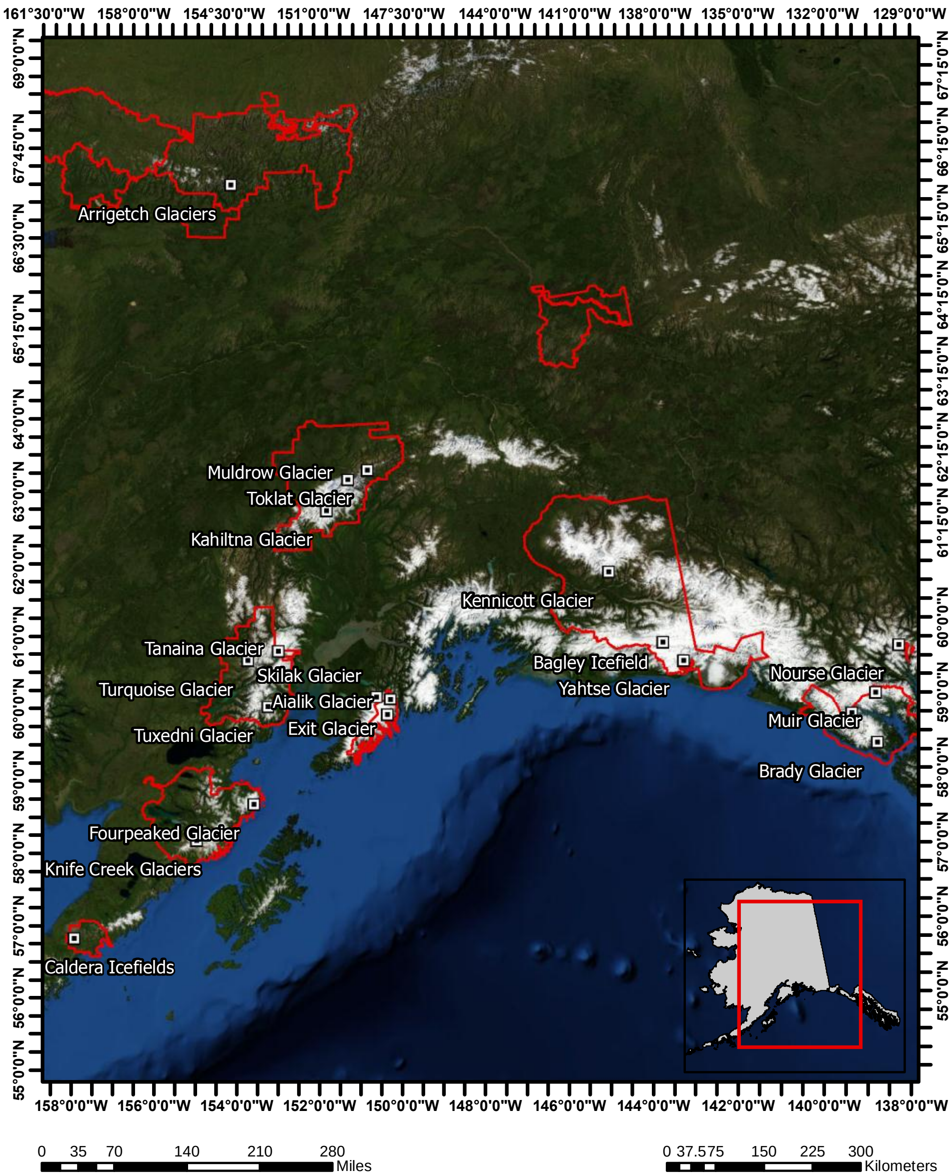


Figure 6. Overview of focus glacier locations. Red polygons are NPS unit outlines.

Glacier Bay: With JT Thomas, Loso visited Glacier Bay between July 7 and 16, 2011. From July 8-11, we traveled by sea kayak up the East Arm to spend 3 days and 2 nights near the Muir Glacier terminus. We spent two days on the NPS research vessel Capelin up the West Arm near the Margerie / Grand Pacific Glacier termini, and on July 15 we traveled to Taylor Bay to spend a day near the Brady Glacier terminus. Loso then visited park headquarters in Bartlett Cove to collect library and GIS resources and to interview local scientists.

Katmai: Thomas and Loso visited Katmai from June 13-19, 2011. The 13th, 14th, and 19th were used for travel to and from Brooks Camp, our base for visiting the Knife Creek Glaciers. While in Brooks Camp, we stayed at the NPS yurt. From the 15th to the 18th, we hiked on foot to the Knife Creek glaciers, backcountry camping during the trip. Fourpeaked Glacier was not visited, and may be a subject of future work.

Kenai Fjords: Loso visited Kenai Fjords on June 3, 2011. The was spent meeting with NPS personnel Fritz Klasner and Deb Kurtz, examining archived data at the office in Seward, and driving out to the Exit Glacier terminus for a short walk at the terminus. Subsequent visits to Aialik Glacier and Skilak Glacier are expected.

Lake Clark: From June 10-12, 2011, Loso visited Lake Clark with JT Thomas and stayed with NPS ranger Rich Richotte in Port Alsworth. We examined archived data with Richotte and also retired NPS staff member Page Spencer at the headquarters there, and on June 12 did an overflight of the focus glaciers with Richotte and Spencer. No landings were made.

Wrangell-St. Elias: Loso visited Wrangell-St. Elias National Park from July 17 to July 30, 2011, accompanied by JT Thomas. From July 17-21, we camped near the terminus of Yahtse Glacier in Icy Bay, accompanying Chris Larsen (permitted separately for his work). We then flew to the BLM Bering Glacier Camp, where we conducted work relevant to this project but outside the park boundary. On July 25, we were picked up at the Bering Glacier Camp by Wrangell Mountain Air and flown to McCarthy, where we spent the following five days examining the Kennicott Glacier during dayhikes.

Results-Mapping

Maps of glacier outlines, with associated geostatistics, were completed for all glaciers in Katmai NP&P and Lake Clark NP&P. In both cases, we expect to refine the datasets, particularly as we acquire additional, higher resolution imagery (some Ikonos tiles for Lake Clark, in particular, were unavailable at the time of this progress report). We demonstrate the current file structure in Appendix C, but defer inclusion of the full datasets until the results are finalized. The analysis presented here is focused on basic metrics of glacier change, but we ultimately plan a more robust analysis of the geostatistical component of the datasets (e.g. Bolch et al. 2010). Results for these two units are summarized sequentially below.

Katmai NP&P

Mapped outlines for Katmai NP&P are shown in Figure 7 and summarized in Table 6. In total, Katmai had 258 glaciers in 1956 (including those partly in, or contiguous with, the park) and 2% more in 2009. We tentatively estimate errors in glacier area to be approximately 10%, with sources of error including imagery resolution (higher resolution imagery increases mapping precision) and differences in image interpretation by technicians (varying greatly among data sources like Landsat, Ikonos, and mapping-era aerial photos). A UAF PhD student is working with us to rigorously quantify these errors, and his analysis will contribute to our final report. Total ice-covered area decreased over that time interval by 15%, from a high of 1066 km^2 in 1956. Estimated total ice volume decreased a similar amount (18%), as would be expected since volumes are here calculated simply by scaling known area changes (Bahr 1997; Radic and Hock 2010). As implied by the overall area changes, terminus retreat was the response seen in most individual glaciers, including notable retreats by Hallo Glacier and others on the Kukak Volcano edifice (Figure 7). Importantly, several glaciers advanced, too, primarily in the area heavily impacted by ash fallout from the 1912 Novarupta eruption.

These overall changes in area are summarized on a per-glacier basis in Figure 8. Ranking glaciers by size (right panel), small to medium-sized glaciers increased in abundance over time while abundance of large glaciers diminished slightly. Ranking them by area-weighted mean elevation (left panel), low-elevation glaciers diminished in abundance while mid to high-elevation glaciers became more common. This increase in abundance of small, high-elevation glaciers is partly caused by breakup of larger glaciers into multiple, smaller tributaries. It is also true, however, that resolution of satellite imagery is different than that of aerial photography used by USGS mappers, and consequent differences in resolvability of small glaciers are also a factor.

Table 6. Summary statistics for glaciers in Katmai NP&P.

Table 6. Summary statistics for glaciers in Katmai NP&P.

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1956)	258	1066	714
Modern (2009)	264	911	587
Absolute Change	6	-155	-127
Percent Change	2%	-15%	-18%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using coefficient/exponent values of 0.2055/1.375 from Radic and Hock (2010).

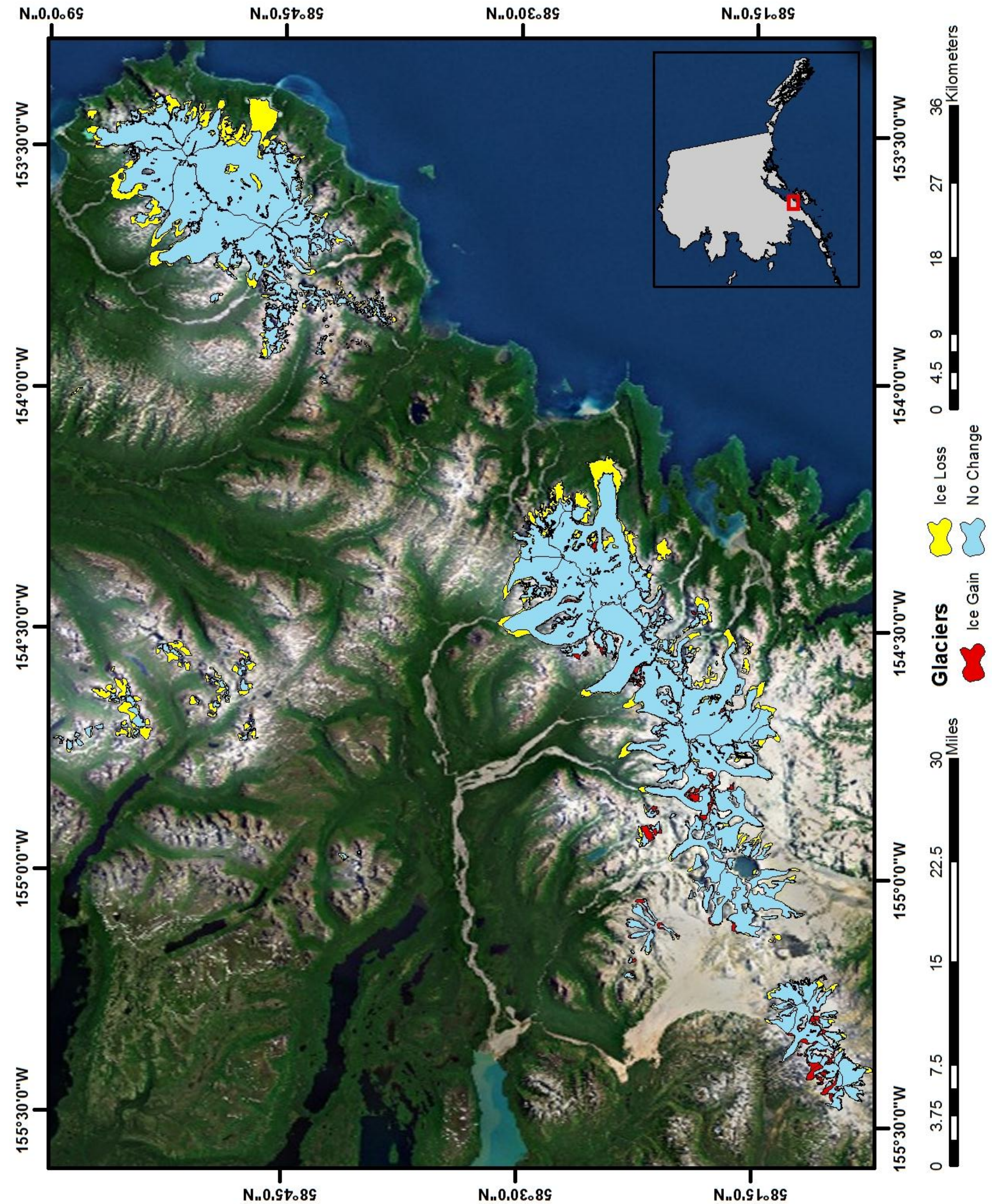


Figure 7. Changes in glacier area between 1956 and 2009 in Katmai NP&P. Note north is to the left in this rotated view.

The pattern shown in Figure 8 highlights the difficulty of using glacier numbers (as opposed to cumulative changes in total area or volume) as a reliable metric of overall glacier change. Cumulative changes in total area of glaciers, by elevation bin, are shown in and probably best reflect the overall change in glaciers in the Park. Above 1300 m, absolute changes in glacier area overall are small, while below there reductions dominate and are substantial. This latter finding primarily reflects the retreat of low-elevation glacier termini, but also probably includes the complete disappearance of some small low-elevation glaciers.

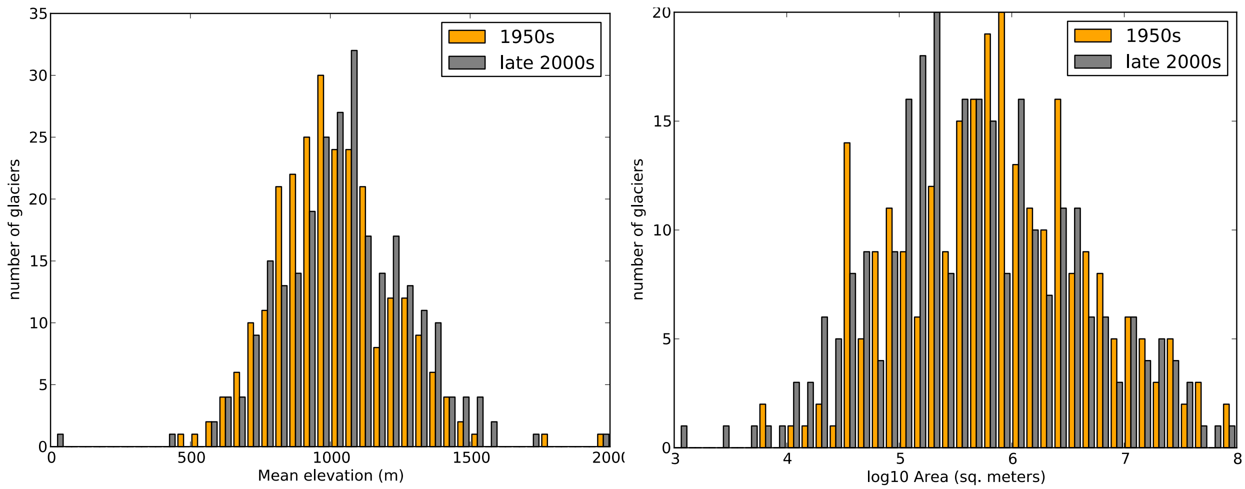


Figure 8. Histograms of changes in number of individual glaciers by area-weighted mean elevation (left) and area (right) in Katmai between nominal dates 1956 ('1950s') and 2009 ('late 2000s').

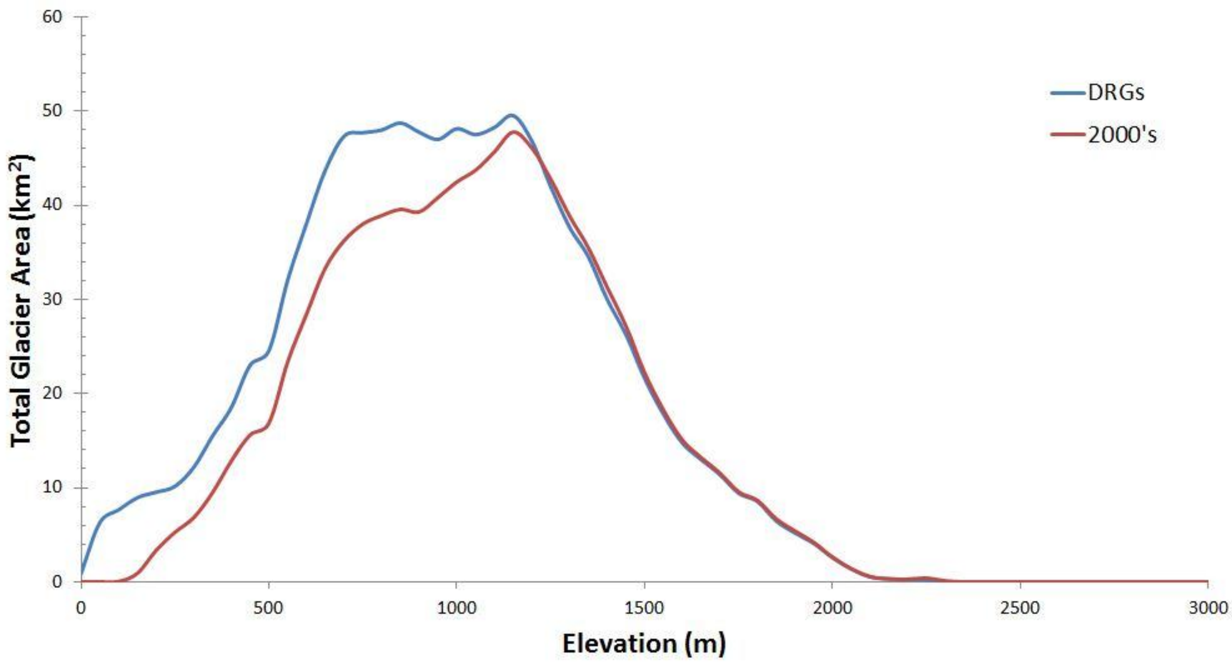


Figure 9. Total area of glacier-covered terrain in Katmai by elevation between nominal dates 1956 ('DRGs') and 2009 ('2000's').

Lake Clark NP&P

Mapped outlines for Lake Clark NP&P are shown in Figure 10 and summarized in Table 7. In total, Lake Clark had 1858 glacier in 1956 and 11% more in 2009. Total ice-covered area decreased over that time interval by 11%, from a high of 3645 km^2 in 1956. Estimated total ice volume decreased 14%. As at Katmai, terminus retreat was the dominant change over this 50-year period. Unlike Katmai, the isolated advances visible in Lake Clark glaciers are probably not explained easily by the effects of ash fallout (although one glacier advance, on the south side of Mt. Redoubt, was on an active volcano). As explained in the “challenges” section later in this report, some of the glacier mapping in the original 1950s era topographic maps appears inconsistent, especially in its treatment of debris-covered ice, and we are hesitant to interpret some of our mapped “advances” as evidence of anything other than cartographic inconsistencies.

Table 7. Summary statistics for glaciers in Lake Clark NP&P.

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1956)	1858	3645	2654
Modern (2009)	2069	3233	2290
Absolute Change	211	-412	-364
Percent Change	11%	-11%	-14%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using coefficient/exponent values of 0.2055/1.375 from Radic and Hock (2010).

These overall changes in area are summarized on a per-glacier basis in Figure 11. Ranking glaciers by size (right panel), small to medium-sized glaciers increased in abundance while abundance of large glaciers was mostly unchanged. Ranking them by area-weighted mean elevation (left panel), low-elevation glaciers diminished in abundance and mid to high-elevation (~>1300 m AWME) glaciers became more common. Cumulative changes in total area of glaciers, by elevation bin, are shown in Figure 12 and again are probably the best indicator of overall change in glaciers in the Park. Above about 1750 m, absolute changes in glacier area overall are minimal, but below that elevation there is a consistent loss of glacier ice as would be expected under a warming climate.

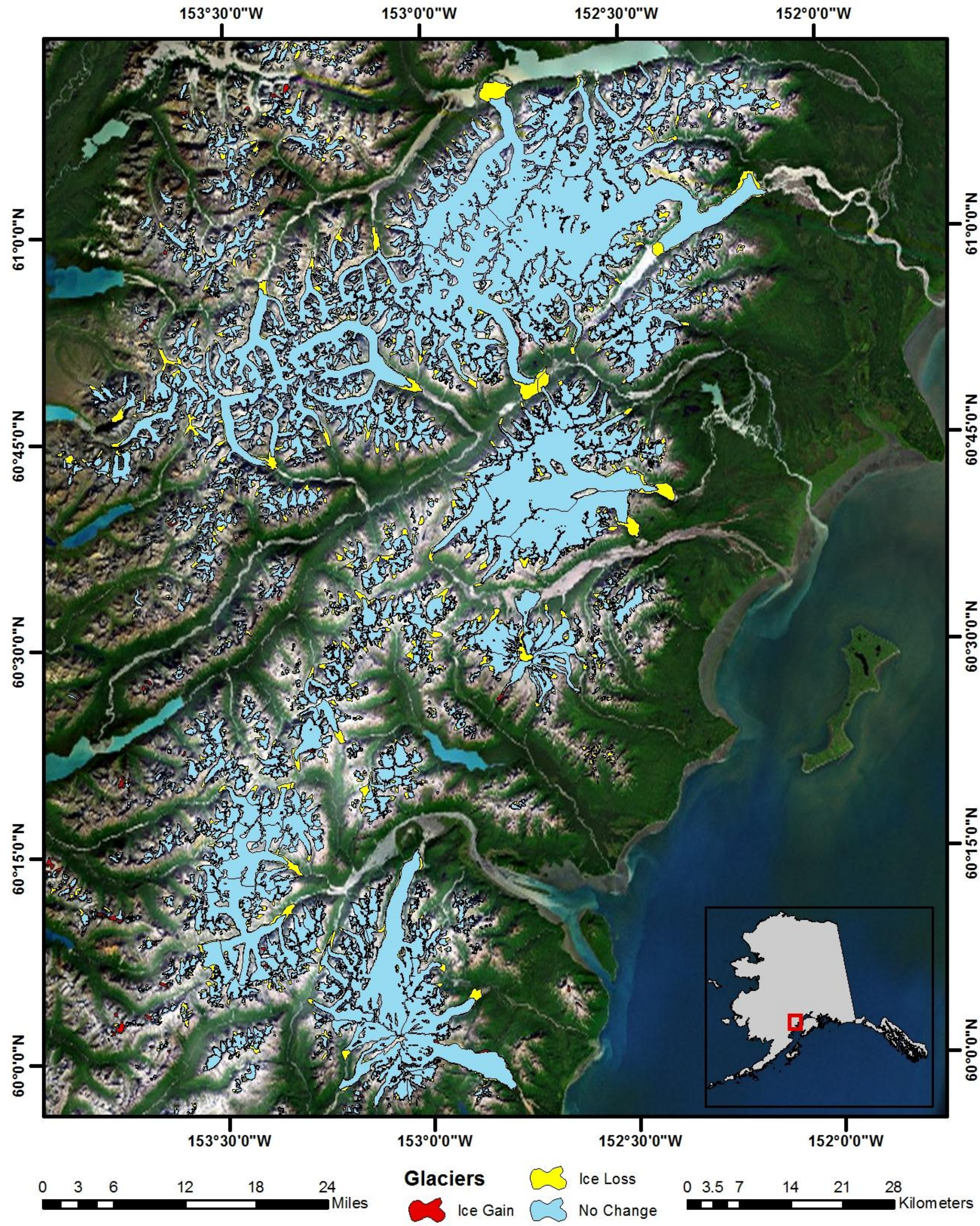


Figure 10. Changes in glacier area between the 1956 and 2009 in Lake Clark NP&P.

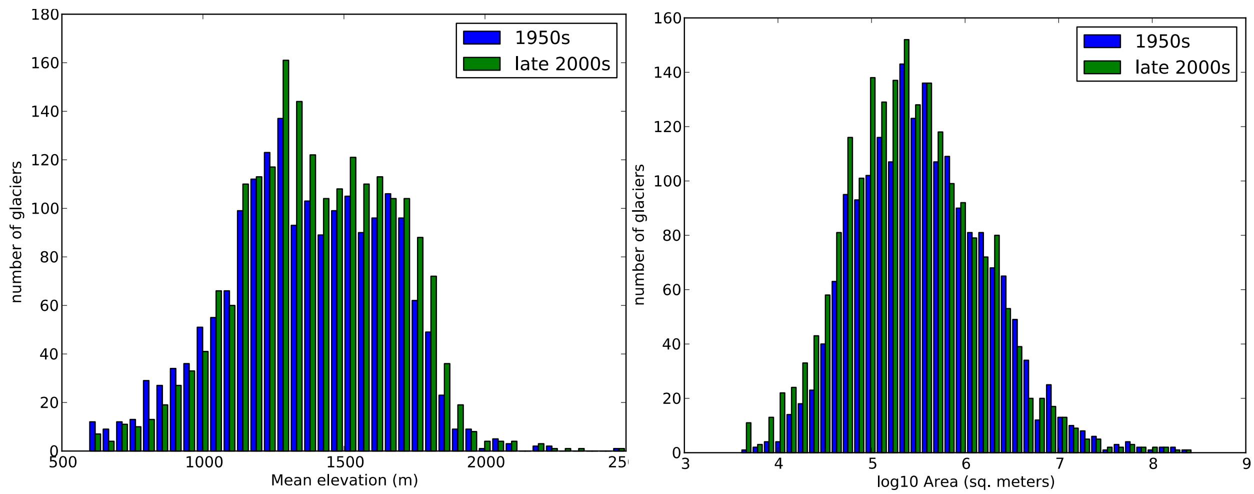


Figure 11. Histograms of changes in numbers of individual glaciers by area-weighted mean elevation (left) and area (right) in Lake Clark between nominal dates 1956 ('1950s') and 2009 ('late 2000s').

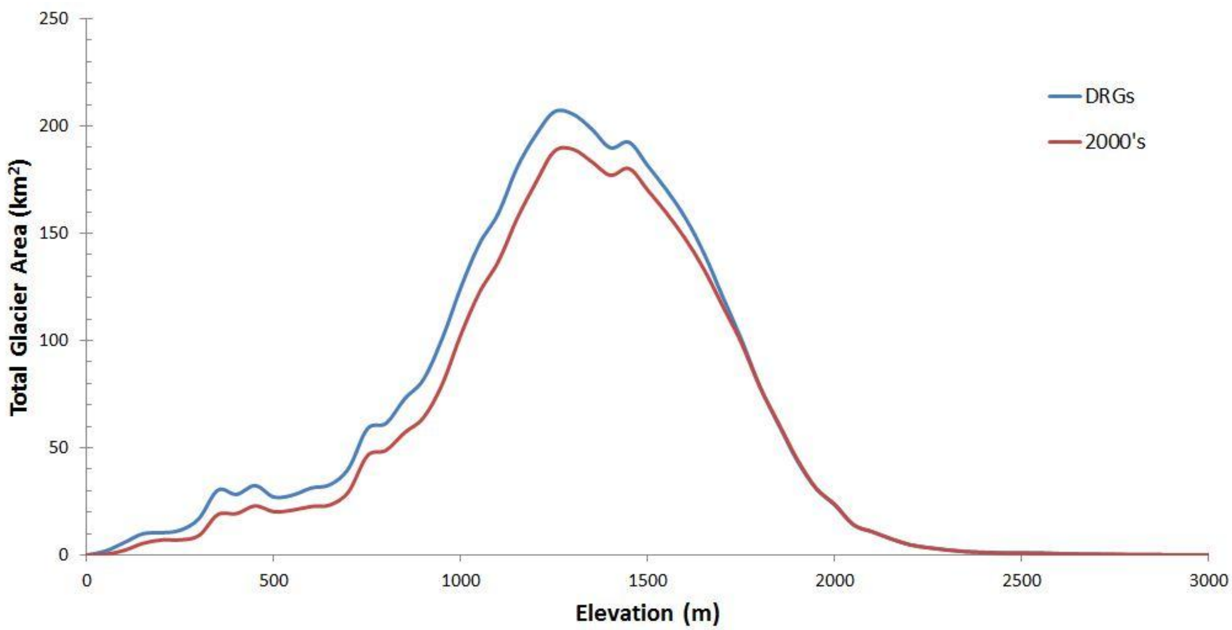


Figure 12. Total area of glacier-covered terrain in Lake Clark by elevation between nominal dates 1956 ('DRGs') and 2009 ('2000s').

Results-Elevation Change

We have completed analysis of surface elevation changes and inferred volume changes for eight glaciers in Lake Clark NP&P over one to two intervals for each glacier, as shown in Table 4. Complete results for those fourteen individual analyses are presented in narrative and graphic form in Appendix A. Below, we begin with the example of Tanaina Glacier over two time intervals between 1996 and 2008 and then move on to summarize broader trends.

Tanaina Glacier (Figure 13) gained an average of 0.03 (±0.01) Gt of ice each year from 1996 to 2001, and then lost 0.10 (±0.02) Gt of ice each year until 2011. Between 1996 and 2001, changes at all elevations were minimal (<1 m) and the glacier geometry was nearly in equilibrium with the regional climate. From 2001 to 2008, however, Tanaina Glacier followed the regional trend of overall mass loss with annual thinning rates exceeding 2 m at lower elevations and approaching zero (no change) only above ~1800 m.

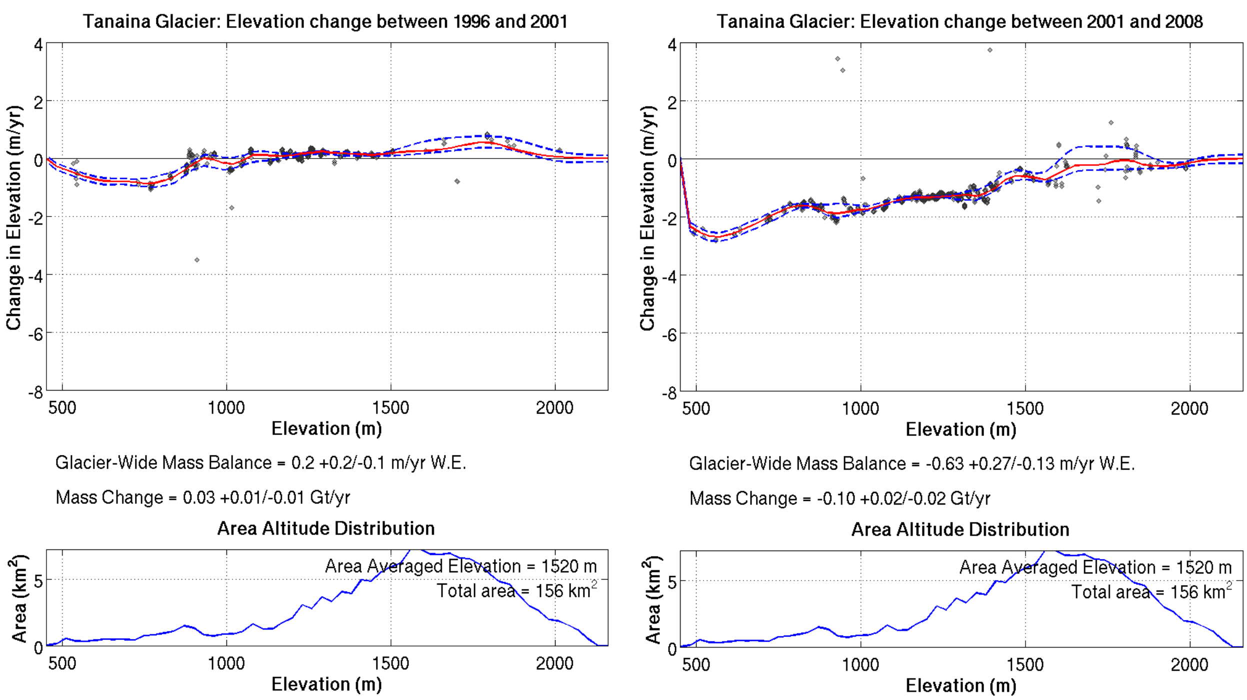


Figure 13. Elevation difference results (above) and area altitude distributions (below) from Tanaina Glacier during two time periods: 1996-2001 (left) and 2001-2008 (right). In upper plots, points are derived from raw laser point data, red lines are median values of a moving window of twelve datapoints, and dashed blue lines are upper and lower quartile values of the moving window.

Glacier-wide mass balance rates provide the most direct way of comparing volume changes on glaciers of different size, and a compilation of such values from all our data reflects the trend suggested by Tanaina Glacier alone (Figure 14). The majority of glaciers sampled between 1996 and 2001 exhibited modestly positive glacier-wide balance rates between 1996 and 2001 (Turquoise, with a rate of -0.70 m/yr w.e. is the only exception). The sampled glaciers show a strong trend towards more negative balance rates in the following 7 years: every sampled glacier had a negative balance rate between 2001 and 2008, with values between -0.5 and -1.5 m/yr w.e.

Averages for each time interval are not plotted, and should be interpreted with caution since the glacier population changed somewhat between intervals, but they reflect the trends noted above: 0.1 m/yr w.e. (1996-2001) and -0.9 m/yr w.e. (2001-2008). On a glacier-by-glacier basis, Turquoise Glacier had the lowest balance in the first time interval and the second lowest balance in the next time interval. Only Tlikakila North Glacier was more negative from 2001-2008.

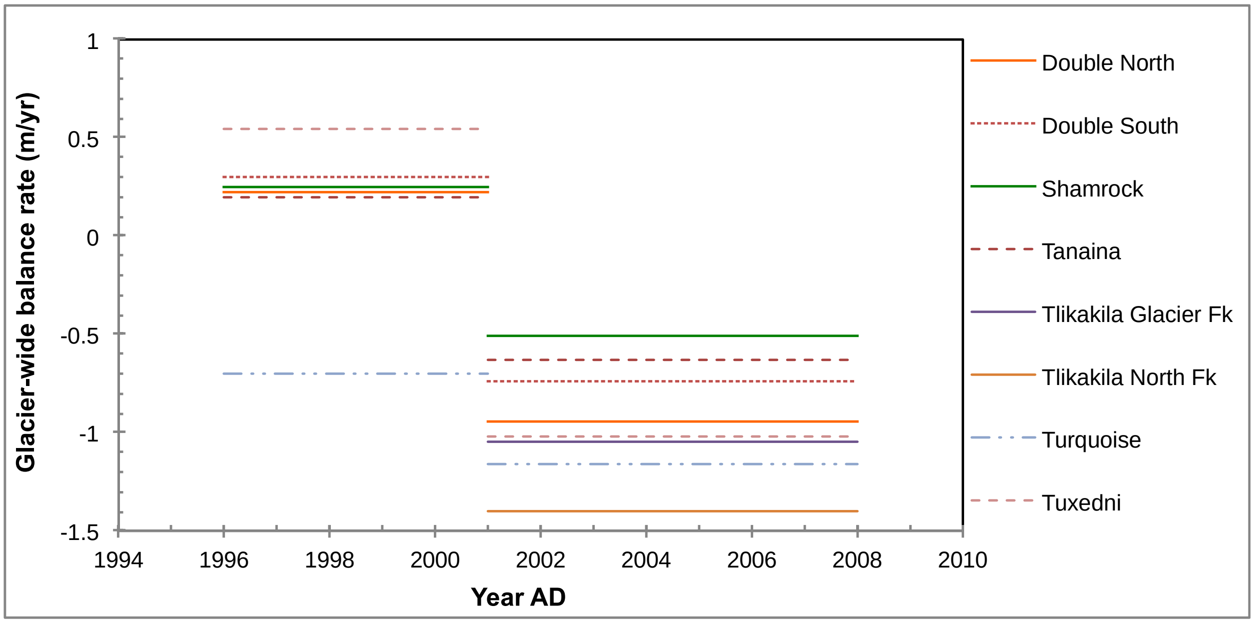


Figure 14. Glacier-wide mass balance rates (m/yr) for eight glaciers from Lake Clark NP&P over multiple time intervals between 1996 and 2008. Confidence intervals excluded for clarity. See appendix A and text for complete details.

Spatial and temporal trends in volume change, by elevation, are shown in Figure 15 and Figure 16. Spatial coverage is somewhat sparser during the early period, 1996-2001, and shows that the upper elevations of all sampled glaciers except Turquoise thickened in that time interval while lower elevations thinned slightly. Tuxedni Glacier, identified by Post (1969) as a surging glacier, appears to be in quiescent post-surge phase during our sampling interval, with a high rate of accumulation zone thickening and conversely high rates of thinning in the ablation zone, presumably recovering from a prior surge-induced redistribution of mass. In contrast, from 2001-2008, Tuxedni (like all the other glaciers sampled) thinned at all except the very highest elevations, yielding a consistent pattern of overall volume loss.

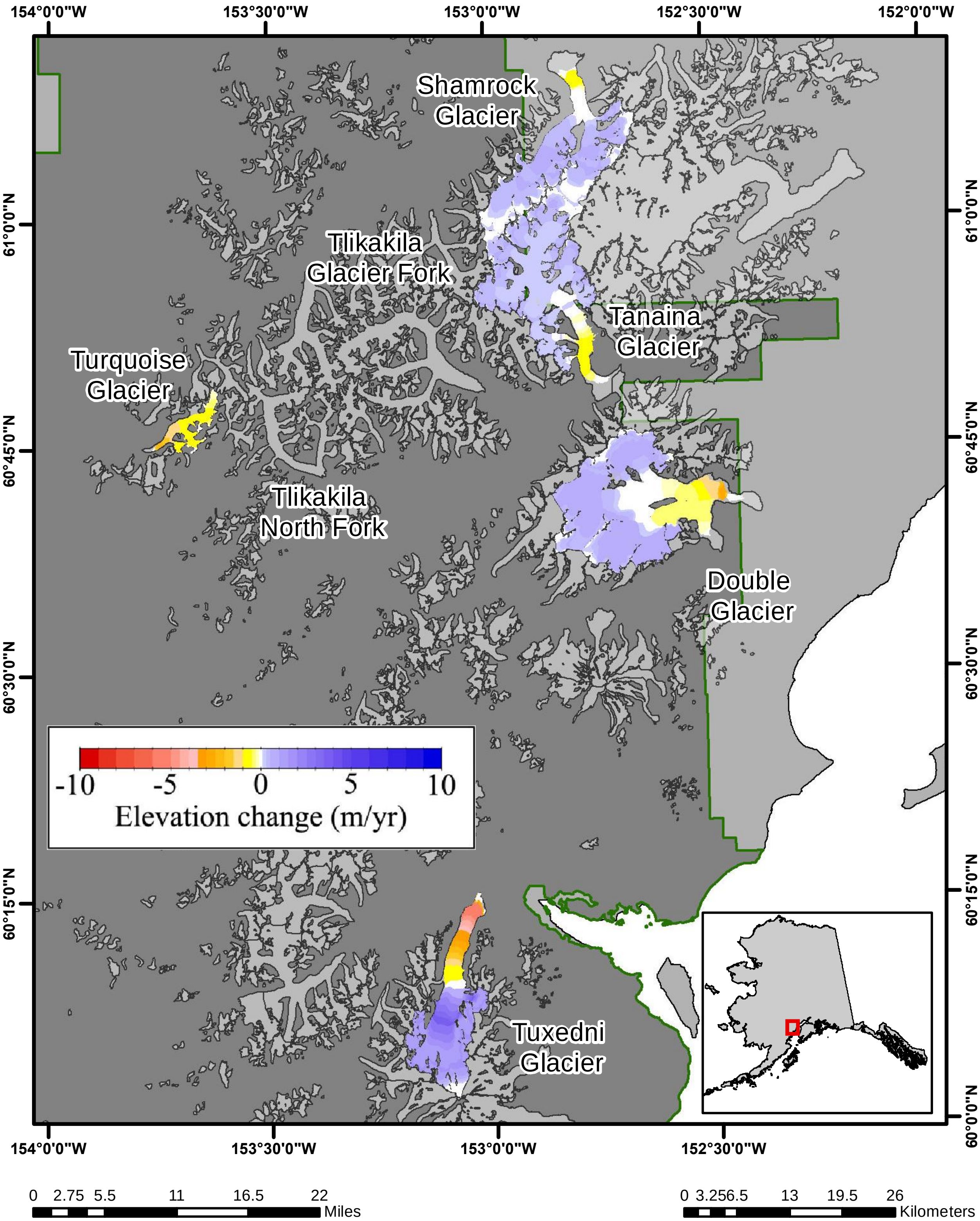


Figure 15. Annual rate of ice thickness change, by elevation, for selected glaciers in Lake Clark National Park and Preserve between 1996 and 2001. See Appendix A for underlying data

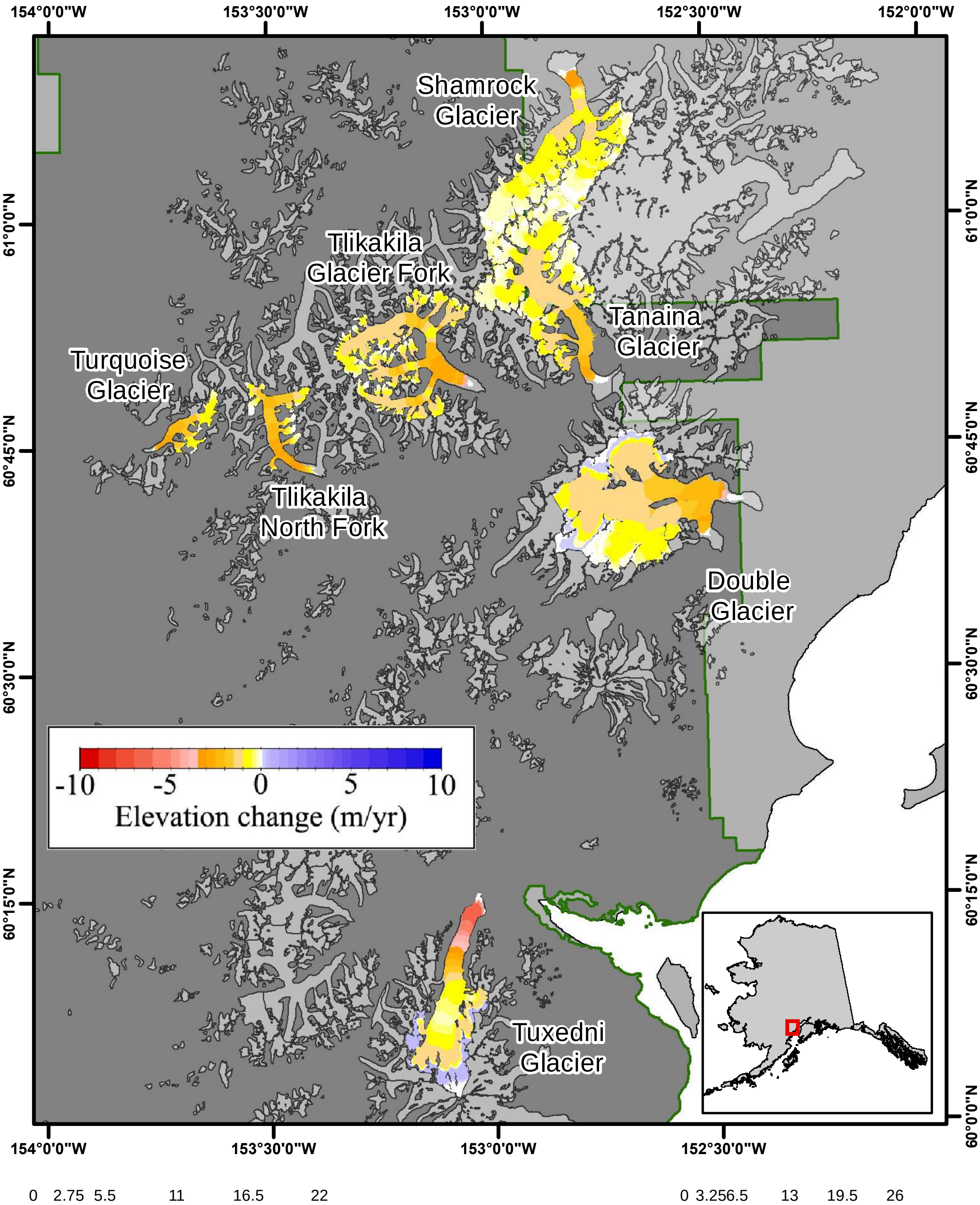


Figure 16. Annual rate of ice thickness change, by elevation, for selected glaciers in Lake Clark National Park and Preserve between 2001 and 2008. See Appendix A for underlying data.

Results-Focus Glaciers

As described earlier, the focus glacier component of this project will culminate in creation of a narrative-based and graphic rich vignette for each glacier. Fieldwork and resource collection associated with creation of these vignettes was described in the methods sections. Creation of the vignettes will primarily be completed during Loso's sabbatical year (fall 2012 – spring 2013), but a sample vignette was constructed for Knife Creek Glacier (Katmai NP&P) to present (in poster form) at the *National Park Service Southwest Alaska Science Symposium*, November 2-4 2011 in Anchorage, AK. The poster itself is included, in reduced form, as Appendix B. Below, we present the four-page vignette and discuss ongoing plans for the focus glacier component of the project.

Sample Vignette

On the following pages, a four-page sample vignette for Knife Creek Glaciers is shown. At present, the final report is envisioned in a format similar to that of Alaska Park Science, 11" wide by 8 ½" tall, on glossy paper. That vision may well evolve in the coming year, but for this first vignette the paper size, design, and format follow the Alaska Park Science model closely. The four pages shown below therefore should be envisioned as two foldout spreads, with the first two pages comprising one spread and the last two comprising the other. Some feedback on these vignettes was received at the meeting and those comments have been incorporated into this vignette. There has been general agreement among all involved parties that individual vignettes will vary from 4-8 pages, depending on the amount of information available for each glacier.

Planning

As noted in the methods section, a few glaciers remain unvisited and somewhat poorly known to the focus glacier author. These include the Caldera Icefields (Aniakchak), Toklat Glaciers (Denali), Fourpeaked Glacier (Katmai), Aialik and Skilak Glaciers (Kenai Fjords), Nourse Glacier (Klondike), and Turquoise Glacier (Lake Clark). Of these, some are well known from the informal and scientific observations of others and can likely be well described without the need for a site visit. Some others have been little described in any literature and may be difficult to describe in a reasonable vignette without a site visit. In this group we include the Caldera Icefields, Fourpeaked Glacier, and Turquoise Glacier. These glaciers are all in the Southwest Area Network (the focus of this progress report) and we suggest that their adequate coverage in the final report depends on either A) location of additional resource materials unavailable at this time to the author, or B) provision of logistical and/or financial support to facilitate site visits in either summer 2012 or summer 2013.

The Knife Creek Glaciers
Katmai National Park and Preserve

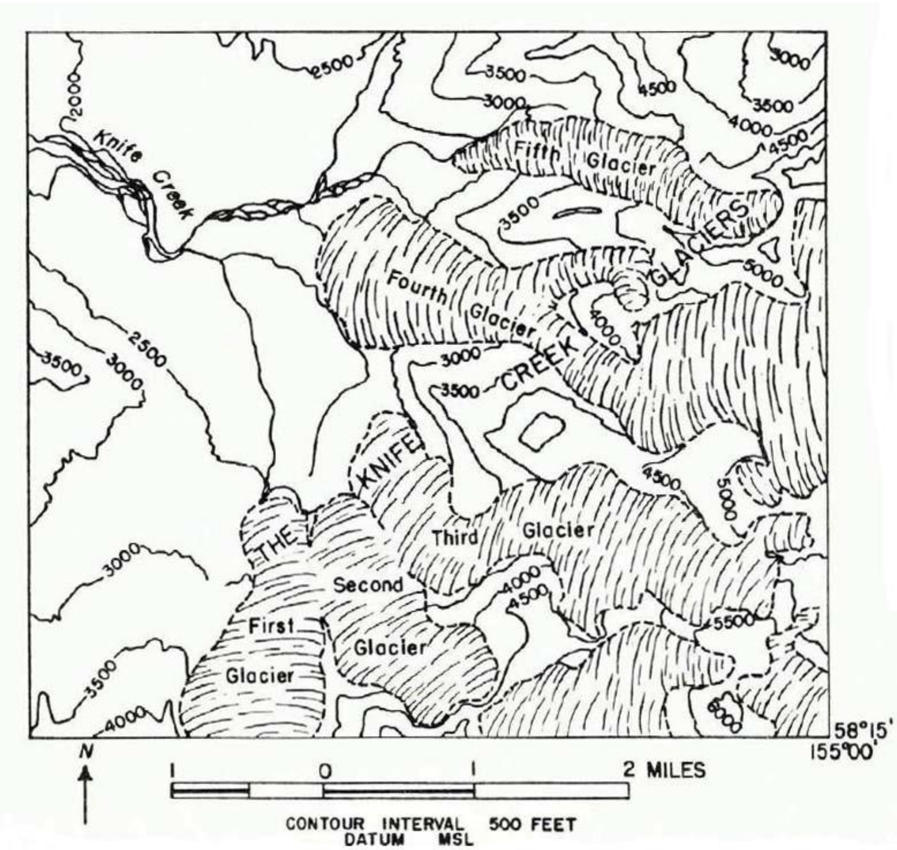


Figure 1 (above). The Knife Creek Glaciers are a complex of small glaciers that drain north and west from Katmai and Trident volcanoes at the head of the Valley of Ten Thousand Smokes. The glaciers, numbered one through five in this map from a 1953 study by Muller and Coulter of the US Geological Survey, were coated in thick layer of tephra after the massive eruption of Novarupta Volcano in 1912.

Figure 2 (left). The tephra-coated terminus of the first Knife Creek Glacier, with a now-abandoned outwash plain in the foreground and the snow-covered slopes of Trident Volcano behind.

The Knife Creek Glaciers

The Knife Creek Glaciers are a complex of related (but not all connected) ice masses that drain north and west from Katmai, Trident, and Griggs volcanoes at the head of the Valley of Ten Thousand Smokes in Katmai National Park and Preserve (Figure 1). The glaciers themselves are modest in size (the largest is <6 km long), and were at one time unremarkable. That all changed between June 6 and 8, 1912, when the world's largest volcanic eruption of the 20th century blanketed the surrounding landscape in a thick layer of volcanic tephra and pyroclastic debris. The volcanic vent (named "Novarupta" by subsequent explorers) was less than 10 km from these glaciers, and they were deeply buried by the volcanic debris.

Volcanoes are common in southwestern Alaska, so prevailing westerly winds ensure that many of southern Alaska's glaciers are regularly coated with volcanic ash--the finest airborne component of tephra. The impacts of this debris on glacier behavior are important and yet poorly documented. Probably most common, because most glaciers are coated only with a very thin (<1 cm) layer of ash after most eruptions, is a temporary decrease in the glacier's albedo (reflectivity) and hence accelerated rates of melt. But the Knife Creek Glaciers were not thinly coated: they were buried with several meters of volcanic debris that persists to this day on all but the highest accumulation zones of the glaciers (Figure 2).

The eruption had another effect on the Third and Fourth Knife Creek Glaciers: the largest of the group (Figure 1). These glaciers originate on the rim of the Katmai volcano caldera. Katmai volcano was not the source of the 1912 eruption, but it did collapse during the eruption as a result of drawdown in the magma chamber beneath the mountain. This caldera collapse removed ~13 km^2 of the mountain summit, effectively "beheading" the Third and Fourth Glaciers, instantaneously removing a substantial portion of their respective accumulation zones (Griggs 1922). How have these glaciers responded to such rough treatment?

Early Research

The first glaciologists to carefully study the Knife Creek Glaciers were Ernest Muller and Henry Coulter, who visited the Valley of Ten Thousand Smokes in 1953 (Muller and Coulter 1957). They mapped the glaciers (see Figure 1), examined the tephra deposits on and near the glaciers, and made measurements of tephra thickness and ablation rates on the Fourth Glacier. Their work (and photos, see repeat photographs on the next page) help us to understand the behavior of the Knife Creek Glaciers in the first 40 years after the eruption.

Muller and Coulter came to the following three conclusions about the Fourth Glacier:
- --Ablation on the Fourth Glacier was greatly reduced by the volcanic debris.
- --The accumulation zone area was greatly reduced by the caldera collapse, resulting in accumulation zone thinning.
- --The reductions in accumulation and ablation rates were roughly balanced, yielding little change in the terminus position in the 40 years since the eruption.

As evidence for the surprising lack of any dramatic change in glacier extent, even decades after the eruption, Muller and Coulter observed that pyroclastic deposits adjacent to the glacier margins remained flat-lying and well-bedded.. They also noted that deposits on the glacier remained largely undisturbed by surficial melting or movement.

Recent Trends

Photos taken in 2011 show that deposits adjacent to the glacier termini remain well-bedded and mostly undisturbed, and also that the glacier margins are no longer in contact with these flat-lying deposits (Figure 3). The glacier surface (visible in the distance) is no longer smooth. How does this compare with maps of terminus change?

Figure 4 shows that the Knife Creek Glaciers (numbers 1-4) have mostly advanced slightly between 1951 and 2000, with terminus changes ranging from 75 meters of retreat on part of Third Glacier to 300 m advance on First Glacier. Area changes associated with these terminus changes are shown in Table 1, and reflect the net growth of the glaciers between 1951 and 2000. Table 1 also shows that the glaciers may be retreating from a late century maximum. Glacier boundaries in 1987 (for clarity, omitted from Figure 4) show that the glaciers 1-4 were all larger in 1987 than in 2000. This may at least partly explain why the glaciers, despite an overall trend of growth in the last 50 years, are partially

Table 1. Glacier areas (km^2) for Knife Creek Glaciers 1 to 4 from 1951 to 2000

Glacier	1951	1987	2000
First	2.83	5.86	5.08
Second	2.85	3.35	3.30
Third	5.64	5.55	5.80
Fourth	9.91	10.44	10.24
All 4	21.24	25.20	24.42

Figure 3. The margin of the First Glacier, looking towards the toe of Fourth Glacier. Note the well-bedded, flat-lying deposits adjancent to the slightly-retreated ice margin at right.

retreated from the well-bedded debris adjacent to their margins (Figure 3).

Figure 4 also shows elevation changes over the same interval, based on the 1951 National Elevation Dataset and the 2000 Shuttle Radar Topography Mission. Most striking (and glacio-logically tangential, at best) are the dramatic elevation gains of the Katmai Caldera lake (filling up) and the Trident Volcano flow complex, which erupted between 1953 and 1959.

More relevant to the glacier story, Figure 4 shows that over 50 years the termini of Knife Creek Glaciers 1, 2, and 4 (and 3 to a lesser extent) have thickened by up to 50 m, while the main body of each glacier is dominated, in contrast, by a pattern of overall thinning. This is consistent with the loss of accumulation area (for glaciers 3 and 4) noted by Muller and Coulter (1957), and with our observation that the glacier termini remain well insulated by a thick layer of tephra.

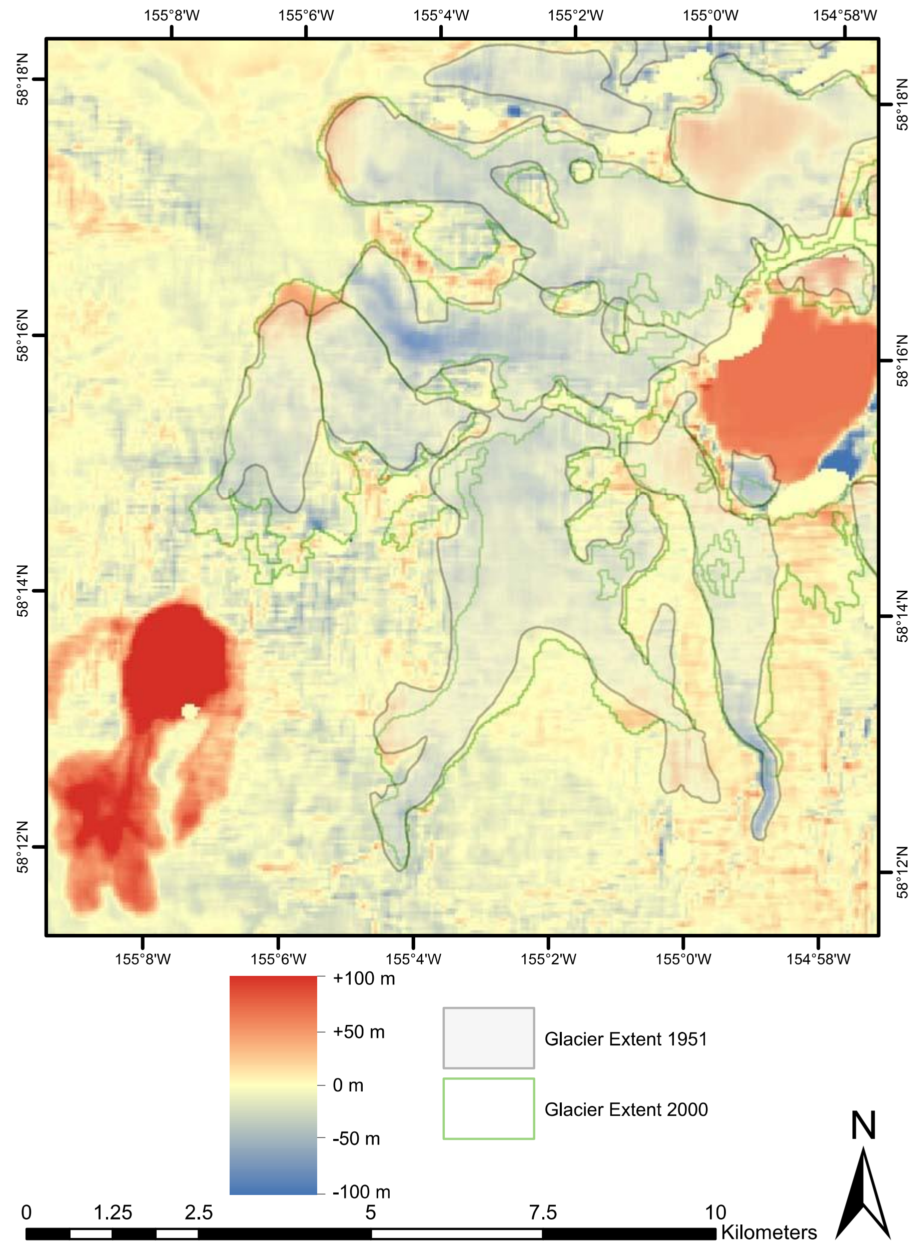


Figure 4. Knife Creek and other nearby glaciers showing glacier boundaries in 1951 and 2000, and changes in elevation from 1951 (from the USGS quad) to 2000 (SRTM).

Photograph by J.T. Thomas

Photograph by E.H. Muller

Figure 5. Repeat photographs of the Knife Creek Glaciers showing them on 15 June, 2011 (above) and 6 July, 1953 (below). Photos taken from approximately 3700 feet on the eastern summit of Broken Mountain, Valley of Ten Thousand Smokes. Snow appears black in the older image.

While thinning, the middle and upper reaches of each glacier have gradually regained a veneer of accumulating snow, exposing their subaerial surfaces once again to atmospheric temperatures and melt.

Repeat Photography

In 2011, we visited the Valley of Ten Thousand Smokes and rephotographed the Knife Creek Glaciers from near the summit of Broken Mountain (Figure 5). The original photo shows continuous ice cliffs demarcating the terminus of each glacier, compared with the more convex and lobate termini in 2011. Upvalley retreat of the glacier margins seems largely to be occurring in distinct embayments that are oriented around terminal streams. Also clear is the enhanced snow cover in the later image, relative to the mostly debris-covered glacier accumulation zones of the 1953 photo. This is partly a result of the 2011 photo being taken 3 weeks earlier in the summer, but field observations suggest that much of the 2011 snow cover is perennial. Note also the interesting and ecologically significant geomorphic evolution of the river courses and outwash plains downstream of each glacier. Since 1953, incision has dominated the behavior of the streams downstream of the Knife Creek Glaciers. And in stark contrast to the similar-appearing forelands of deglaciated terrain downstream from Alaska's many retreating glacier termini, the foreland here has undergone very little colonization by plants (Figure 6)--evidence of the stark difference between primary succession on volcanic debris and on freshly deglaciated terrain.

References

Griggs RF (1922) The Valley of Ten Thousand Smokes. Washington, National Geographic Society.

Muller EH and Coulter HW (1957) The Knife Creek glaciers of Katmai National Monument, Alaska. *Journal of Glaciology* 3:116-122.

Fenner CN (1926) The Katmai magmatic province. *Journal of Geology* 34:675-771.

Eichelberger J (2006) The Valley of Ten Thousand Smokes, Alaska, including Katmai, Trident, and Novarupta Volcanoes, Katmai National Park. Alaska, The Alaska Volcano Observatory.

Figure 6. 100 years later, the terrain around the Knife Creek Glaciers is barely vegetated.

Discussion

Preliminary Highlights

The data presented here are preliminary, but serve well to document our approach to, and progress on, this project. Some of the details of our analytical techniques are still evolving, but the general presentation has now been vetted in several meetings and one prior progress report. Accordingly, the language and structure of this progress report is largely similar to the previous one and our focus here has been on documenting new datasets. The following trends emerge from this preliminary work.

- Katmai NP&P was 5.2% glaciated in the early period (nominally 1956), but ice cover diminished 15% by the modern period (2009), to become 4.4% glaciated (911 km^2).
- Lake Clark NP&P was 22.2% glaciated in 1956, but ice cover diminished 11% by the modern period, to become 19.7% glaciated (3233 km^2).
- The vast majority of glaciers in both parks have shrunk considerably, mainly by terminus retreat, in that time. The total number of glaciers, in contrast, has grown in both parks. This may be partly an artifact of differing map/imagery quality, but it largely reflects the breakup of large glaciers into multiple smaller ice masses.
- In Katmai NP&P, a significant minority of glacier termini in the Kejulik Mountains advanced after 1956. We attribute most of these advances to lingering effects (primarily reduced ablation) of ash deposition from the 1912 Novarupta eruption.
- Only one significant terminus advance occurred in Lake Clark NP&P since 1956, on the south side of Redoubt Volcano. Around and south of Little Lake Clark, several small glaciers that grew significantly or "appeared" since 1956 may reflect cartography errors in the original maps.
- Using laser altimetry, we measured 14 distinct intervals of elevation change distributed among eight glaciers in Lake Clark NP&P from 1996 - 2001 and/or 2001 - 2008. During the earlier interval, all but one glacier (Turquoise) had slightly positive glacier-wide mass balance rates (overall thickening). In the later interval, every glacier had negative rates (overall thinning).
- The lowest measured balance rate (greatest thinning) was on Tlikakila North Glacier from 2001-2008: ice loss averaged 1.40 m/yr over the entire glacier surface.
- We visited eleven and photographed two other focus glaciers in summer 2011. Resources sufficient for construction of vignettes are now available for all focus glaciers except the Aniakchak Caldera Icefields, Fourpeaked Glacier, and Turquoise Glacier.
- A sample vignette for the Knife Creek Glacier has now been vetted by NPS personnel and project collaborators, and will serve as the model as we commence planning for the layout and design phase for the final report.

Challenges

As this project progresses, new challenges and questions emerge. Our goal in including them here is to open a discussion about these items. We itemize these challenges below, in no particular order.

- High-resolution imagery continues to be of great value for this project, and we are finding that it results in some significant changes in our interpretation of glacier extent compared to both map and Landsat derived outlines. This imagery also allows us to zoom in to a greater extent, thereby significantly increasing the amount of time required for digitization. To date, we have received most of the high-resolution imagery from NPS after spending considerable time making outlines from Landsat imagery. This is an inefficient way for us to do our work, and we would like to streamline this process in the future so that we have all available imagery in hand before starting a particular region. We are aware of the desire to update previously completed regions as we acquire better imagery, but we do not want to do so at the expense of meeting upcoming deadlines.

- We are beginning to question whether our time spent to meet the cumbersome data formatting requirements of GLIMS is a good investment. We find that data users often approach us directly after having difficulty working with GLIMS-formatted data online. As an alternative, we have made some efforts to host the data at GINA, which is desirable due to the cleaner data interface and the fact that we can work with people locally. Our initial meetings with GINA have not led to concrete activity to host the data, however we can work more on this in the future. GINA generally requires some funding from investigators to help support their time, and this might be one issue that is stalling progress. In any case, we would like to have additional feedback from NPS on this matter, as we are not clear on the importance of broad data dissemination versus internal hosting of data on NPS servers.

- We originally included glacier slope and aspect as glacier parameters, however for some glaciers these data are misleading. In particular, we were finding slope values to be ranging from 30 to 90 degrees for some glaciers, which is physically implausible. One problem may be that steep, high elevation regions are biasing the glacier-wide values. Rather that distribute potentially misleading information, we decided not to distribute those fields yet. We are presently working on better ways to characterize glacier slope and aspect, including a presentation of these parameters by elevation bin.

- Also noted in the prior report but still without clear resolution is the best method to track changes in area of individual ice masses. Labels for ice masses are based on the location of the polygon centroid, which changes over time. Additionally, ice masses often split during glacier retreat, so that one ice mass becomes two. Less often, they merge. In this way, tracking individual masses and total numbers of glaciers is both problematic and can be deceiving. The challenge can be visualized in Figure 17. We maintain that the geographic coordinates of the glacier centroid are the least ambiguous way of tracking ice masses, but some NPS participants are still uncomfortable with this approach. This may require further discussion.

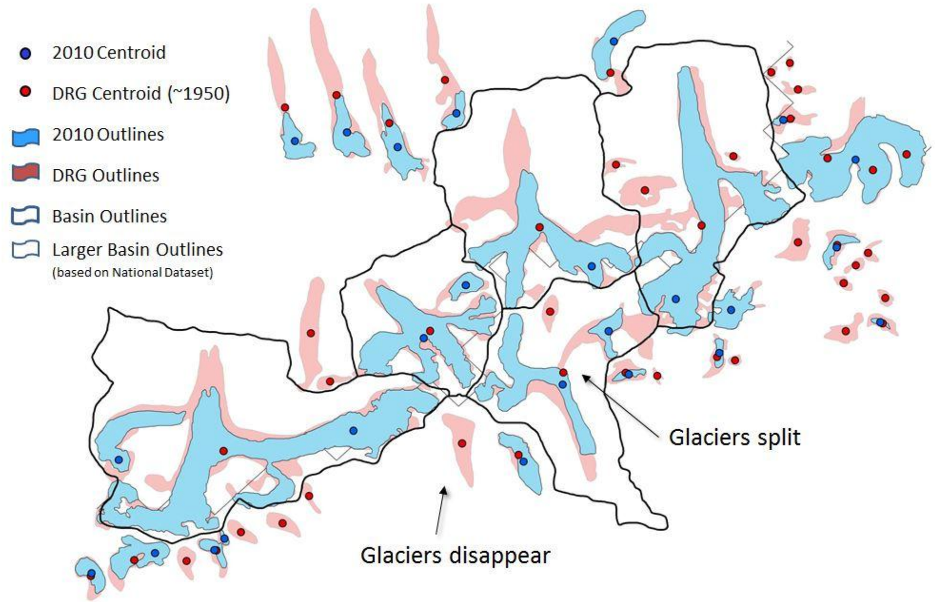


Figure 17. Individual glaciers are labeled according to a point located at the centroid of the polygon. When a glacier retreats and splits into two different glaciers, it receives a different label and so is no longer possible to track the evolution of that single glacier through time. A similar problem occurs when two glaciers advance and merge into one. Examples of both are shown here.

- As noted in the previous progress report, there are a few focus glaciers about which we are aware of very little historical literature: the Aniakchak Caldera, Fourpeaked Glacier, and Turquoise Glacier. To a lesser extent, we are also concerned about resources for Skilak Glacier and Tuxedni Glacier. Our concern is that we have very little to say about these glaciers. NPS could help significantly by helping to a) identify data and other resources we may have missed, and b) considering options for facilitating site visits to these glaciers, perhaps in combination with other existing NPS missions.

- NPS has acquired internal funding for layout and design of the final report, but printing and distribution plans—including funding for same—remain unclear. Before finalizing a contract for layout and design, we would like to discuss and confirm these plans.

- Some of the topographic mapping, especially on ash and debris-covered glaciers, seems to reflect unusual variability in what was mapped as glacier ice. This probably reflects a combination of variable aerial photo quality and technician variability. It is outside our scope to remap the DRG-based glacier outlines, but we note this here (with an example, Figure 18) to alert our NPS collaborators—who may wish to verify some 1950's outlines. Similarly, we struggle to consistently map ash and debris-covered ice when alternating between Landsat and Ikonos imagery. We illustrate the challenge in Figure 19.

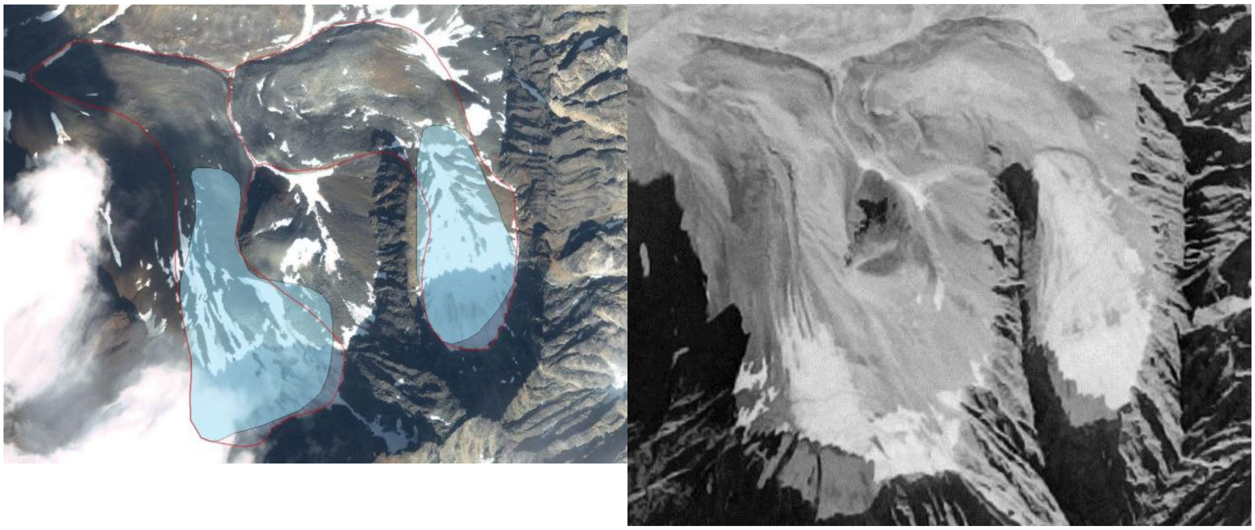


Figure 18. Example of consistency issues with respect to 1950s era glacier mapping. The Ikonos image at left shows modern snow and debris-covered ice as mapped by us (red outlines) and 1950s mapping of glacier outlines from DRGs (blue outlines). At right, the 1957 aerial photo upon which the DRG was based shows that the early cartographer mapped visible ice only on the right lobe, but visible ice plus *some* debris-covered ice on the left lobe.

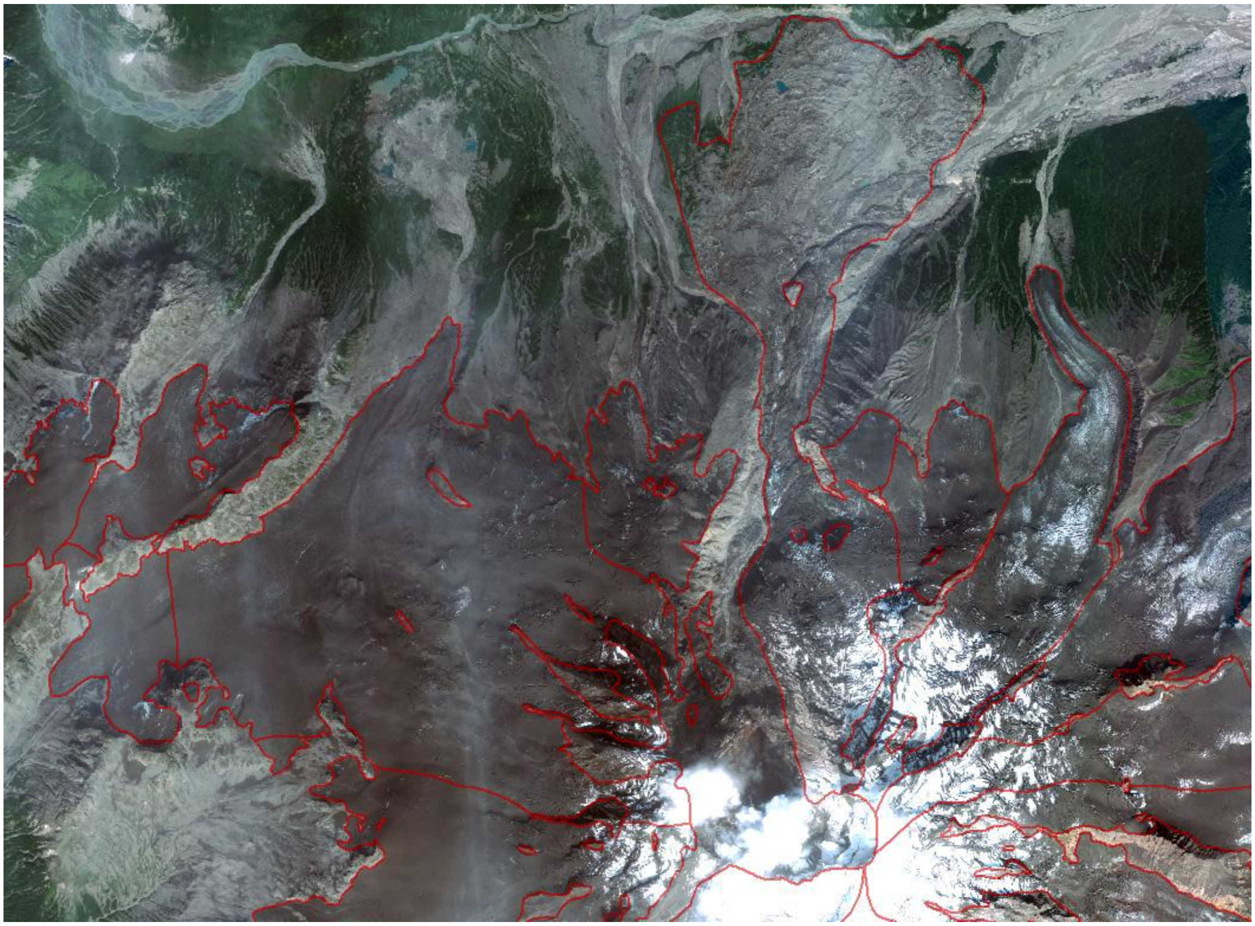


Figure 19. Ash-covered ice on Mt. Redoubt, with modern ice mapped as red polygons on an Ikonos base image. Accurately delineating the ice on Landsat imagery would be very difficult, a challenge we must contend with due to our use of both satellite products in this project.

Literature Cited

Arendt AA, Echelmeyer KA, Harrison WD, Lingle CS, Valentine VB (2002) Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* 297: 382-386

Bader H (1954) Sorge's Law of densification of snow on high polar glaciers. *Journal of Glaciology* 2: 319-323

Bahr DB, Meier MF, Peckham SD (1997) The physical basis of glacier volume-area scaling. Journal of Geophysical Research 102: 20355-20362

Bolch T, Menounos B, Wheate R (2010) Landsat-based inventory of glaciers in western Canada, 1985-2005. *Remote Sensing of Environment* 114: 127-137

Cogley JG, Hock R, Rasmussen LA, Arendt AA, Bauder A, Braithwaite RJ, Jansson P, Kaser G, Moller M, Nicholson L, Zemp M (2011) Glossary of Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, 114 pp

Echelmeyer KA, Harrison WD, Larsen CF, Sapiano J, Mitc hell JE, DeMallie J, Rabus B, Adalgeirsdottir G, Sombardier L (1996) Airborne surface profiling of glaciers: a case-study in Alaska. *Journal of Glaciology* 42: 538-547

Molnia BF (2001) Glaciers of Alaska. *Alaska Geographic* 28:1-11

Post A (1969) Distribution of surging glaciers in western North America. *Journal of Glaciology* 8: 229-240

Post A, Meier MF (1980) A preliminary inventory of Alaskan glaciers, in World Glacier Inventory Workshop, 17–22 September 1987, Reideralp, Switzerland, Proceedings: International Association of Hydrological Sciences (IAHS) Publication No. 126, p. 45–47

Paul F, Barry RG, Cogley JG, Frey H, Haeberli W, Ohmura A, Ommanney CSL, Raup B, Rivera A, Zemp M (2009) Recommendations for the compilation of glacier inventory data from digital sources. *Annals of Glaciology* 50: 119-126

Radic V, Hock R (2010) Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *Journal of Geophysical Research* 115: doi:10.1029/2009JF001373

Sapiano JJ, Harrison WD, Echelmeyer KA (1998) Elevation, volume and terminus changes of nine glaciers in North America. *Journal of Glaciology* 39: 582-590

Winkler GR. 2000. A Geologic Guide to Wrangell-St. Elias National Park and Preserve, Alaska. USGS Professional Paper 1616, 166 pp.

Appendix A: Elevation and Volume Change Analyses

Narrative summaries of elevation changes for individual glaciers during discrete time intervals are followed by plots of all summarized data.

Double Glacier (1996, 2001, 2008)

1996 – 2001: The cumulative changes of the entirety of Double Glacier showed little change between 1996 and 2001. Below 1000m elevation the elevation change was negative and gradually decreased from ~0m of change at 1000m to -3m/yr change at 600m elevation. Glacier elevation increased slightly with a maximum increase of ~1m/yr over the range 1000 – 1700m. The cumulative effect of these changes was a slightly positive mass balance (0.21 +0.14/-0.13 m/yr w.e.) and mass change (0.04 +/- 0.03 Gt/yr) during the time period.

2001 – 2008: Double glacier showed significant elevation loss during this period, which is made more dramatic by relatively little change between 1996 and 2001. Below 1400m elevation, Double Glacier showed ~2m/yr of elevation loss with slightly less loss above 800m and slightly more below 800m. The elevation data suggests loss above 1400m as well, but the increased variability in the elevation data above 1400m suggest that this elevation loss may not be not as uniform across the glacier as it is at lower elevations. The mass balance and mass change of Double Glacier between 1996 and 2001 were both negative (-0.83 +0.42/-0.31 m/yr w.e. and -0.17 +0.06/-0.06 Gt/yr, respectively), reflecting the significant elevation loss below 1400m.

Both halves of Double glacier (referred to here as Double North and Double South) were flown separately in all three years (1996, 2001, 2008). However, only minor differences in elevation changes exist between the two halves of the glacier and so they are not discussed separately here.

Shamrock Glacier (1996, 2001, 2008)

1996 – 2001: Between 1996 and 2001, Shamrock Glacier showed little overall change in elevation with only a slight decrease in elevation below 900m and a slight increase above 900m. The downward elevation change reached a maximum of ~-1.5 m/yr at the glacier toe (~600m elevation) with the magnitude of change decreasing to ~0 m/yr at ~900m elevation. Above 900m elevation, the elevation change was generally positive and relatively constant at ~0.5 m/yr from ~900m up to ~1900m. The uppermost areas of Shamrock Glacier (1900m to 2000m) showed near zero to slightly positive (< 0.1 m/yr) elevation change between 1996 and 2001. Mass balance and mass change were both slightly positive during this period (0.25 +0.12/-0.13 m/yr w.e. and 0.03 +0.02/-0.02 Gt/yr, respectively).

2001 – 2008: With a trend similar to Double Glacier, Shamrock Glacier showed noticeably more negative elevation change between 2001 and 2008 than it did between 1996 and 2001. In the lowest elevation areas of Shamrock Glacier (~550m to 800m), elevation change was most negative with values reaching ~-3.8 m/yr. Above 800m, elevation changes remained negative between 2001 and 2008, but less so than at lower elevations. Elevation change in the elevation range of 800 to 1800m were typically ~-1 m/yr. Above 1800m Shamrock showed little overall elevation change between 2001 and 2008, with some highly variable data at the uppermost extent of Shamrock Glacier. Mass balance and change were both negative for Shamrock Glacier between 2001 and 2008 (-0.51 +0.19/-0.13 m/yr w.e. and -0.06 +0.02/-0.02 Gt/yr, respectively).

Tanaina Glacier (1996, 2001, 2008)

1996 – 2001: Between 1996 and 2001, Tanaina glacier showed only small changes in elevation. Below 900m to the lower extent of the glacier at 500m, the typical elevation loss was ~-1 m/yr. For elevations above 900m to the upper glacial extent at ~2100m, Tanaina Glacier showed slightly positive elevation changes of ~0.2 m/yr to ~0.5 m/yr. Glacier-wide mass balance and mass change were both slightly positive between 1996 and 2001 (0.2 +0.2/-0.1 m/yr w.e. and 0.03 +0.01/-0.01 Gt/yr, respectively).

2001 – 2008: Following the regional trend, Tanaina Glacier showed more significant elevation loss between 2001 and 2008 than between 1996 and 2001. Elevation change was most negative at the lowest areas of the glacier (~500m to ~700m) with rates ranging from ~-2 to ~-3 m/yr. Above this, the magnitude of elevation change gradually decreased until it was approximately zero near 1800m elevation. This overall negative elevation change led to significantly negative mass balance and mass change between 2001 and 2008, with values of -0.63 +0.27/-0.13 m/yr w.e. and -0.10 +0.02/-0.02 Gt/yr, respectively.

Tlikakila Glacier Fork (2001, 2008)

2001 – 2008: The Tlikakila Glacier Fork Glacier (?) showed similar trends of elevation change between 2001 and 2008 as other glaciers in the Lake Clark region. Elevation changes were predominately negative with only one limited area at ~925m elevation that showed positive elevation change. However, based on the deviation from the overall trend of elevation change on the glacier, the positive elevation change of this area may be due to measurements errors or the presence of irregular topographic features on the glacier. Unfortunately we do not currently have data to further explore these possibilities, and so we include the data in this analysis since it does not affect the overall elevation change results. The elevation change is most negative (-4 m/yr) at the lowest extent of the glacier (~600m elevation) and decrease gradually in magnitude to -1 m/yr at ~1600m elevation. While the glacier contains area above 1600m, these areas were not sampled by the field measurements and so the data is not available. Based on the measured elevation changes, the mass balance and mass change between 2001 and 2008 were -1.05 +0.18/-0.25 m/yr w.e. and -0.11 +0.03/-0.03 Gt/yr, respectively.

Tlikakila North Fork (2001, 2008)

2001 – 2008: Following the regional trend, the Tlikakila North Fork Glacier showed significant elevation loss between 2001 and 2008. Elevation changes were most negative in lower regions of the glacier (650m to 800m elevation) with changes becoming slightly less pronounced with increasing elevation to be -2 m/yr at 1400m. Unfortunately the glacier is poorly sampled above 1400m due to the topography of the glacier despite significant glacial area above 1400m. Based on the glacial area sampled, the mass balance and mass change were significantly negative with values of -1.40 +0.32/-0.48 m/yr w.e. and -0.04 +0.01/-0.01, respectively.

Turquoise Glacier (1996, 2001, 2008)

1996 – 2001: Unlike most other glaciers in Lake Clark, between 1996 and 2001 Turquoise Glacier showed significant loss of elevation over most of the glacier. The most significant elevation loss occurred at the lowest elevations of the glacier with a value of ~-2.5 m/yr at 1100m elevation. This decrease lessened with increasing elevation such that elevations typically decreased by ~-1 m/yr from 1400m to 1800m. Above ~1800m data coverage is more sporadic, but the decrease in elevation continues to lessen with values ~-0.5 to ~0 m/yr above 1800m. The resulting mass balance is -0.70 +0.10/-0.09 m/yr w.e., which is significantly negative. However, the mass change is less dramatic, due to the small size of the glacier, at only -0.01 +/- 0.00 Gt/yr. Note that the +/- 0.00 uncertainty results in converting and rounding the small changes in ice mass to the Gt/yr units.

2001 – 2008: Between 2001 and 2008, Turquoise Glacier showed more dramatic elevation loss than between 1996 and 2001. Hence, Turquoise Glacier remained in the regional trend of elevation loss during these time periods despite showing more elevation loss between 1996 and 2001 than is otherwise typical for Lake Clark glaciers. The most severe elevation loss occurred at the lowest extents of the glacier, with losses of ~3 m/yr below 1300m elevation. Moving up glacier from 1300m, the elevation loss generally decreased in magnitude to a minimum of ~-0.5 m/yr at ~1650m. In the upper extents of the glacier, above ~1650m, the elevation loss remains relatively constant at ~-0.5 to ~-0.7 m/yr. The resulting mass balance and mass change were negative with values of -1.16 +0.28/-0.22 m/yr w.e. and -0.02 +/- 0.00 Gt/yr, respectively.

Tuxedni Glacier (1996, 2001, 2008)

1996 – 2001: Tuxedni Glacier is a known surging glacier (e.g. Post, 1969). The pattern of Tuxedni elevation change during this period suggests that it was primarily in a quiescent phase between 1996 and 2001. The elevation change profile shows severe elevation loss at lower elevations (<500m) where the largest elevation loss of ~-6 m/yr occurred at ~200m elevation. The elevation change increased dramatically from this minimum up to a maximum increase in elevation of ~4 m/yr at ~700m. Above 700m, the elevation change generally settles out to ~1.5 to ~2 m/yr until the elevation data becomes highly variable above 1500m. This elevation change profile is typical of a surging glacier in a quiescent phase. The high values of elevation loss at low elevations reflect the loss of ice that moved down the glacier during the surge. Conversely, the high elevation gain at the higher elevation reflects the recovery of the glacier from the surge as the recovery dominates over climate or other drivers of ablation. Despite the severe elevation loss at low elevation, Tuxedni Glacier maintained a positive mass balance and mass change between 1996 and 2001 with values of 0.53 +0.42/-0.38 m/yr w.e. and 0.05 +0.03/-0.03 Gt/yr, respectively.

2001 – 2008: Between 2001 and 2008, Tuxedni Glacier appears to still be in a quiescent period, but elevation loss has generally remained the same increased across the glacier. Below 700m, the pattern of elevation change remained relatively similar to the pattern between 1996 and 2001, with the maximum elevation loss of -~-7 m/yr occurring at ~200m. The magnitude of elevation loss decreased dramatically up to ~700m where it levels off to ~0 m/yr. However, unlike between 1996 and 2001, above 700m Tuxedni shows little to no increase in elevation. Instead, above ~750m the elevation change again becomes negative with a typical value of ~-1 m/yr. Above ~1100m the data become sporadic, but suggest the elevation changes at the upper extents do not become strongly positive. The increased elevation loss at higher elevations is reflected in the mass balance and mass change results with values of -1.14 +0.22/-0.45 m/yr w.e. and -0.10 +0.04/-0.04 Gt/yr, respectively.

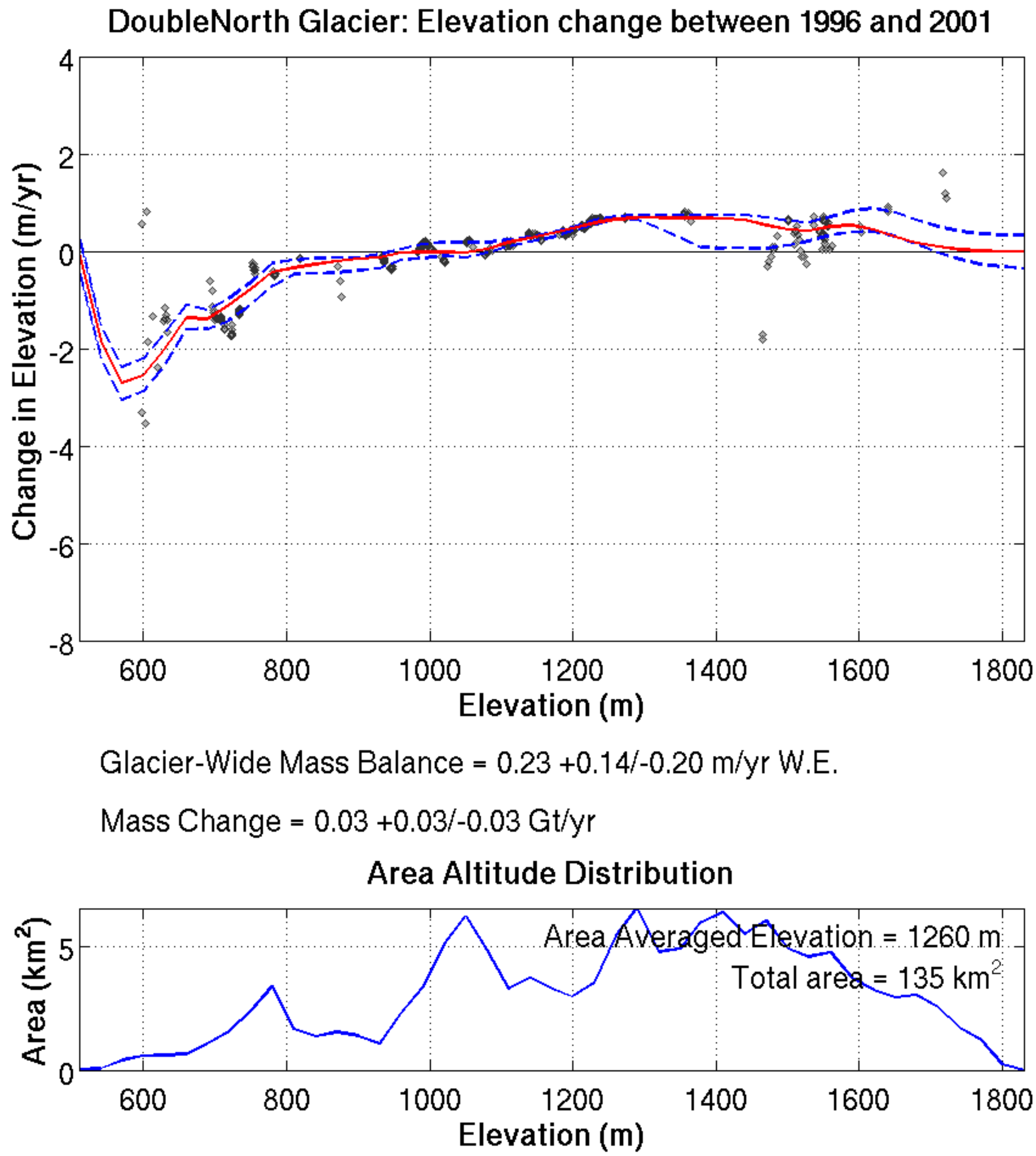


Figure A1. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Double North Glacier 1996-2001.

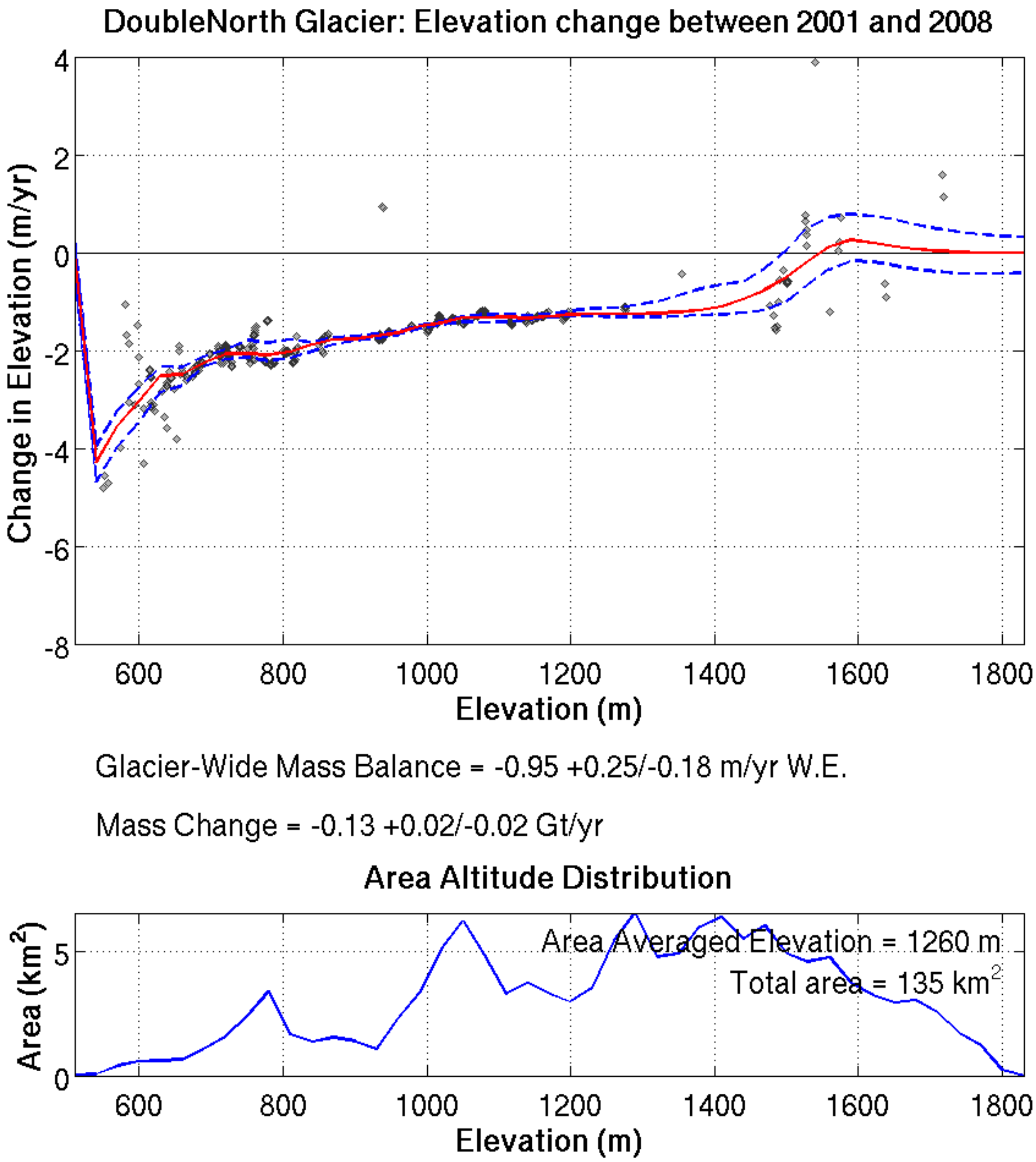


Figure A2. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Double North Glacier 2001-2008.

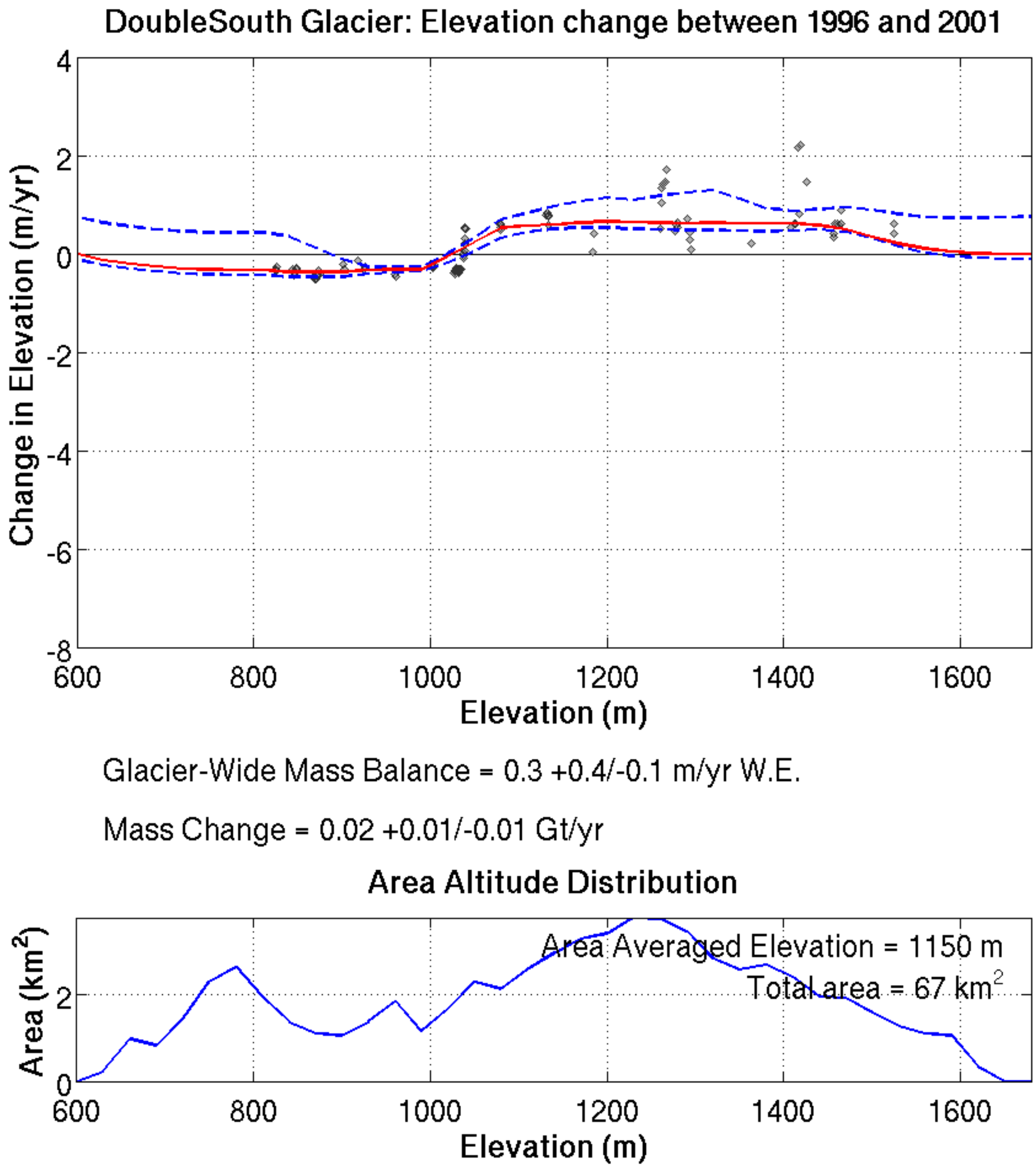


Figure A3. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Double South Glacier 1996-2001.

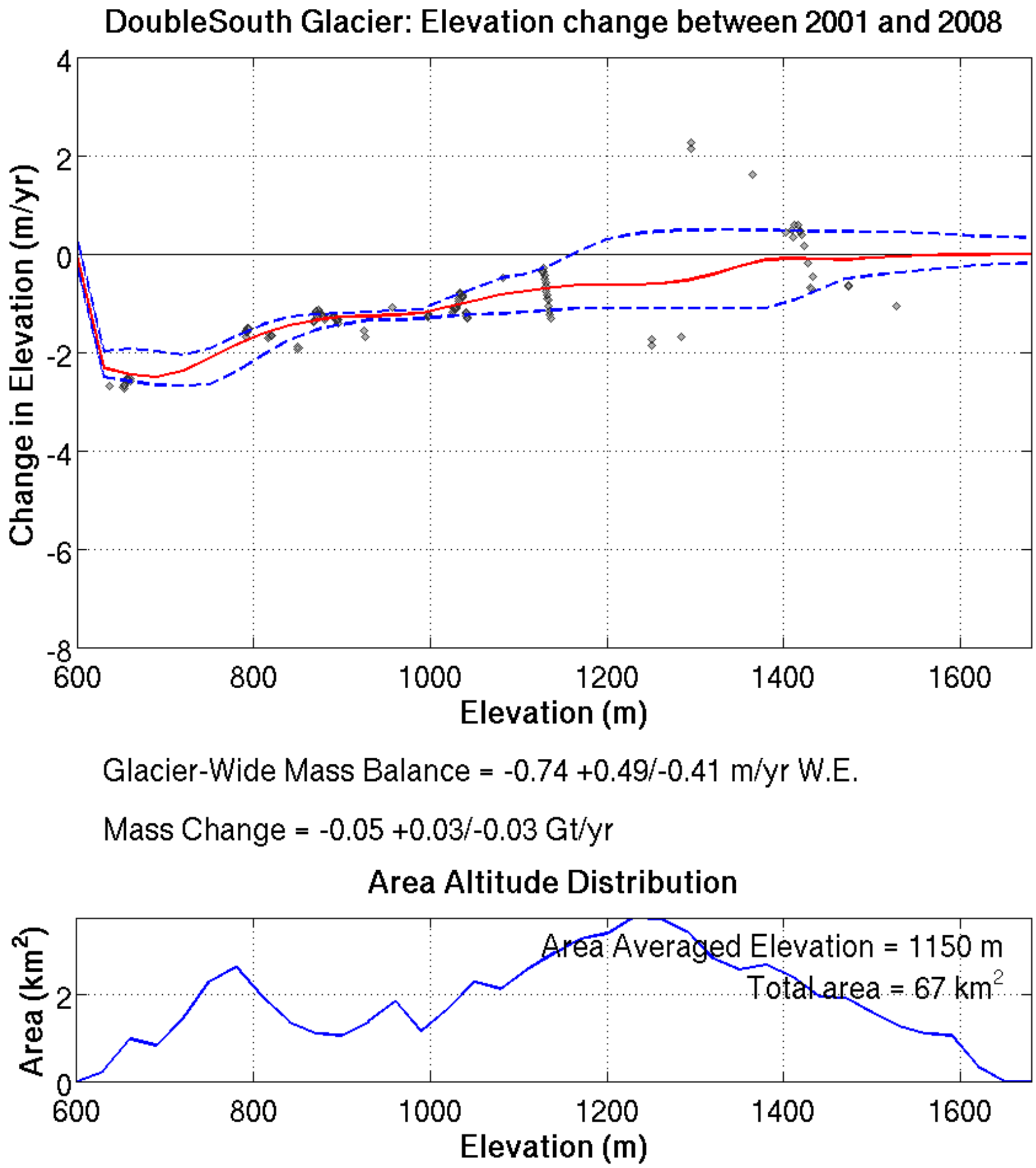


Figure A4. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Double South Glacier 2001-2008.

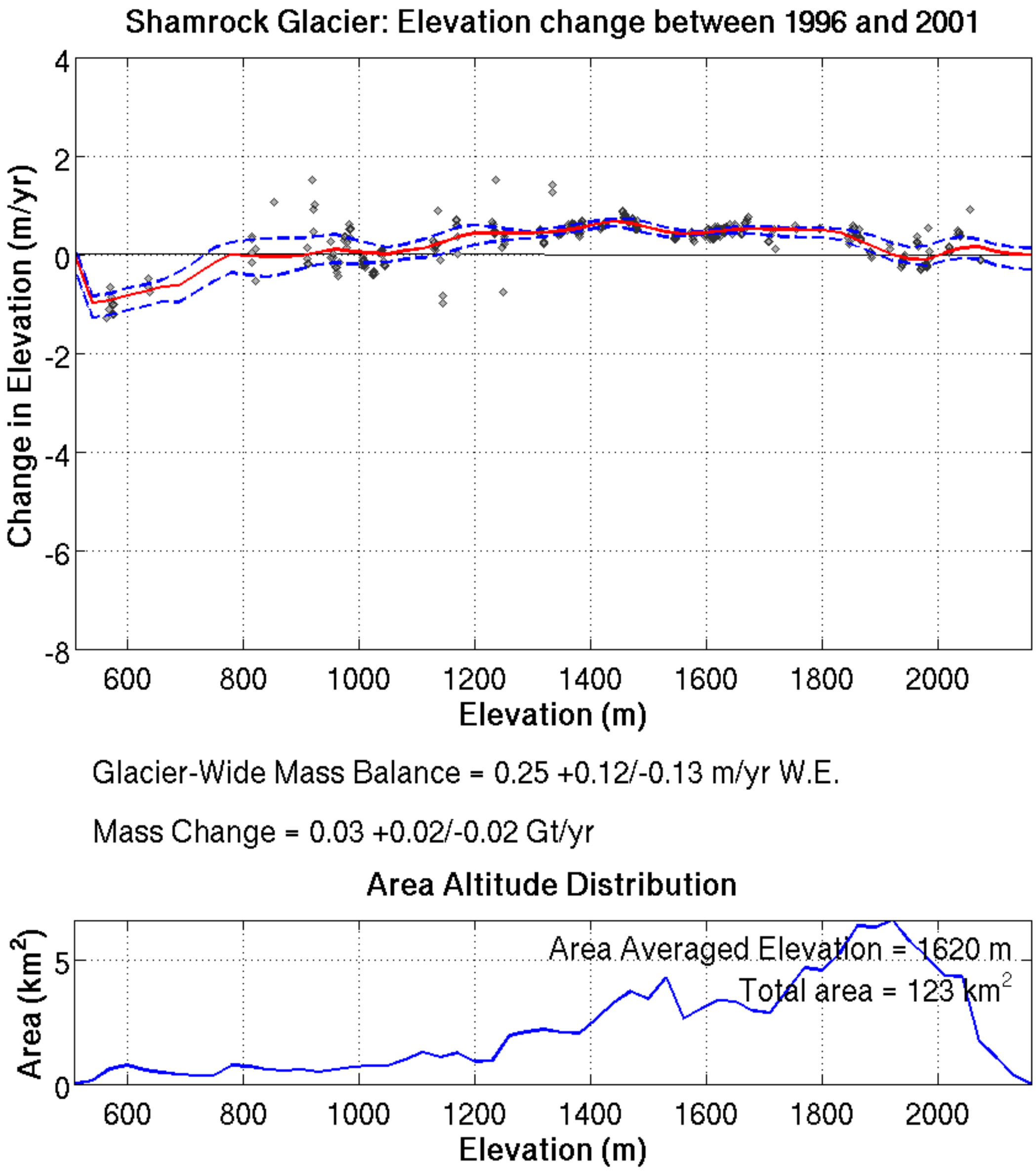


Figure A5. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Shamrock Glacier 1996-2001.

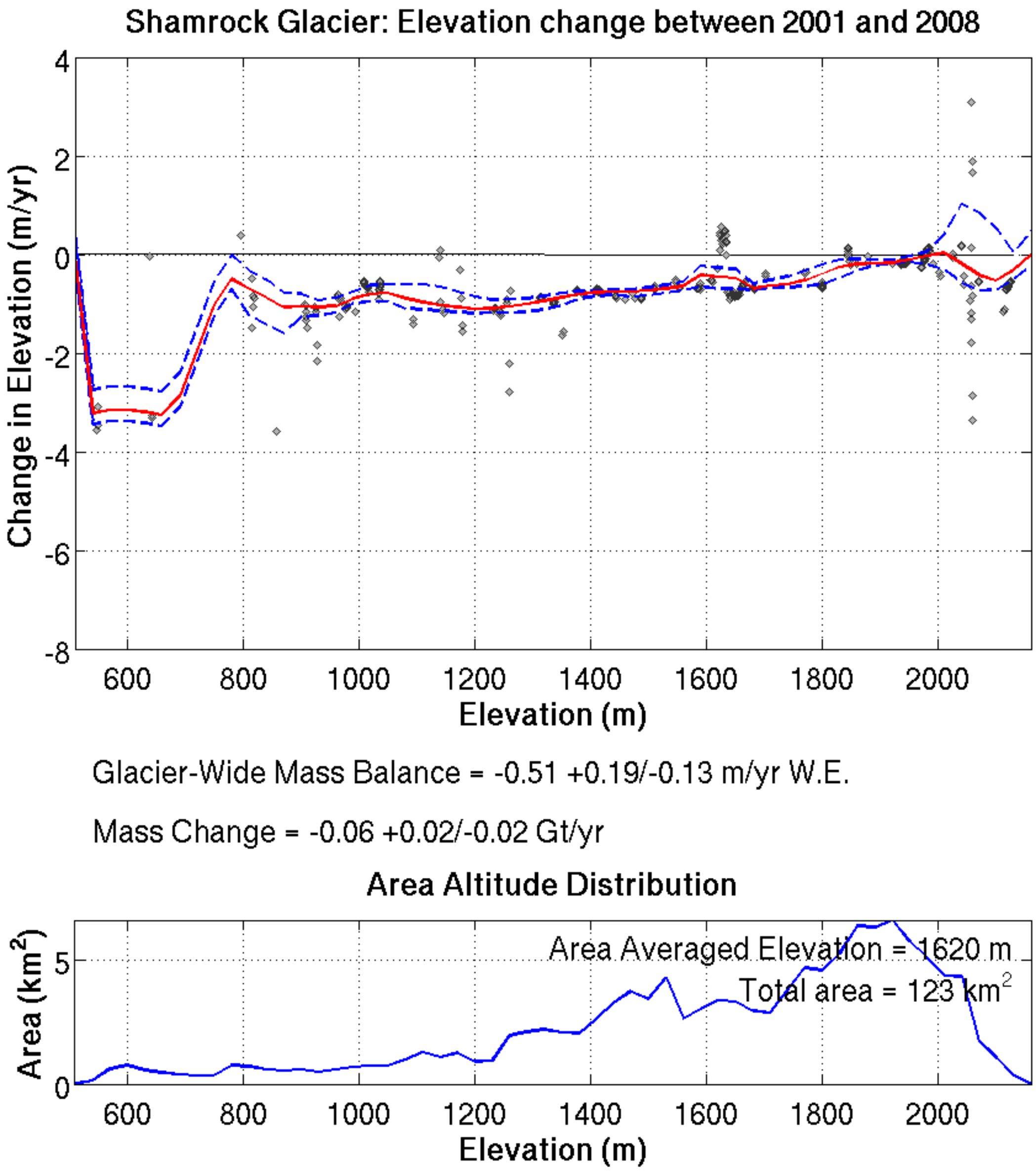


Figure A6. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Shamrock Glacier 2001-2008.

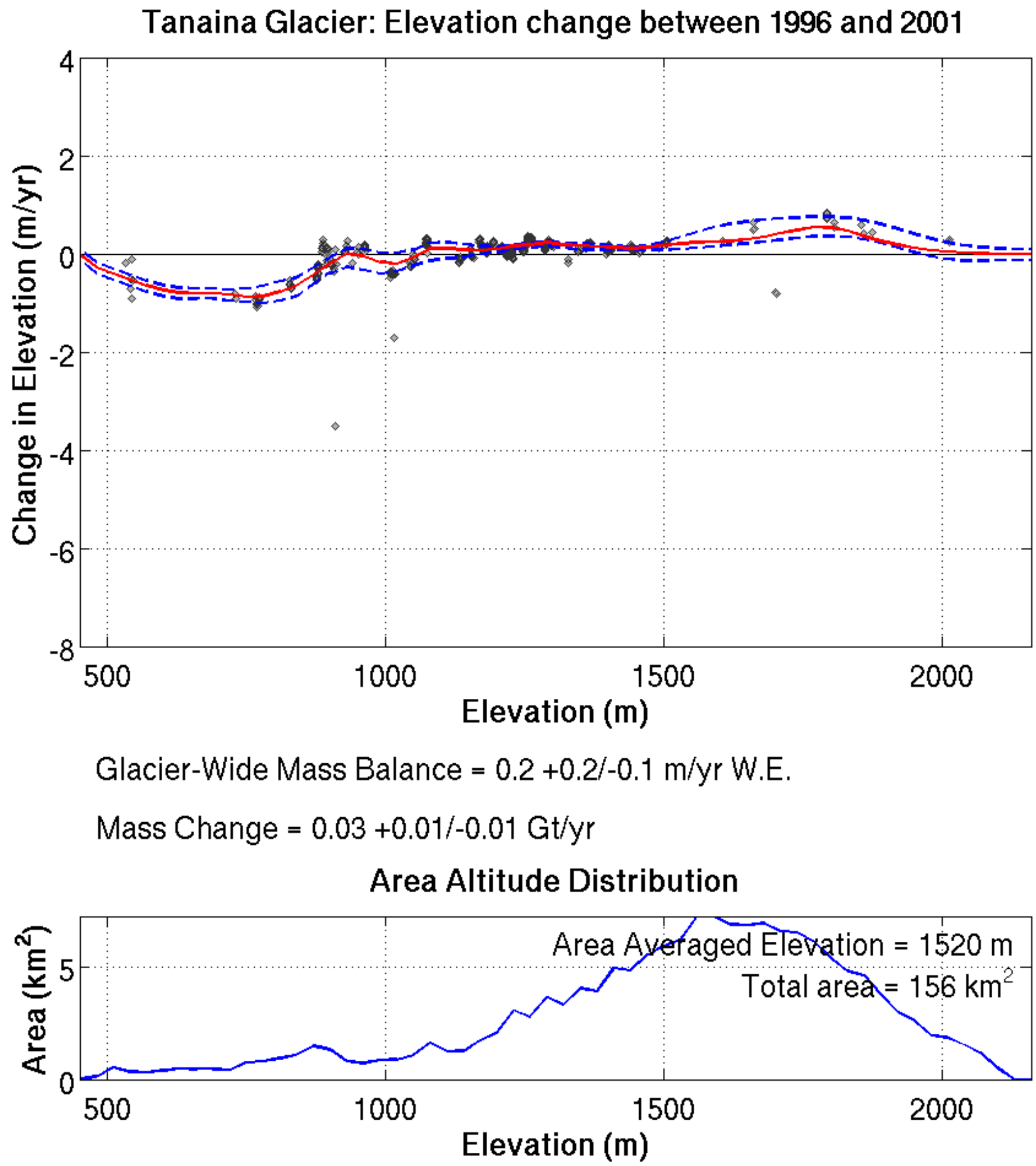


Figure A7. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tanaina Glacier 1996-2001.

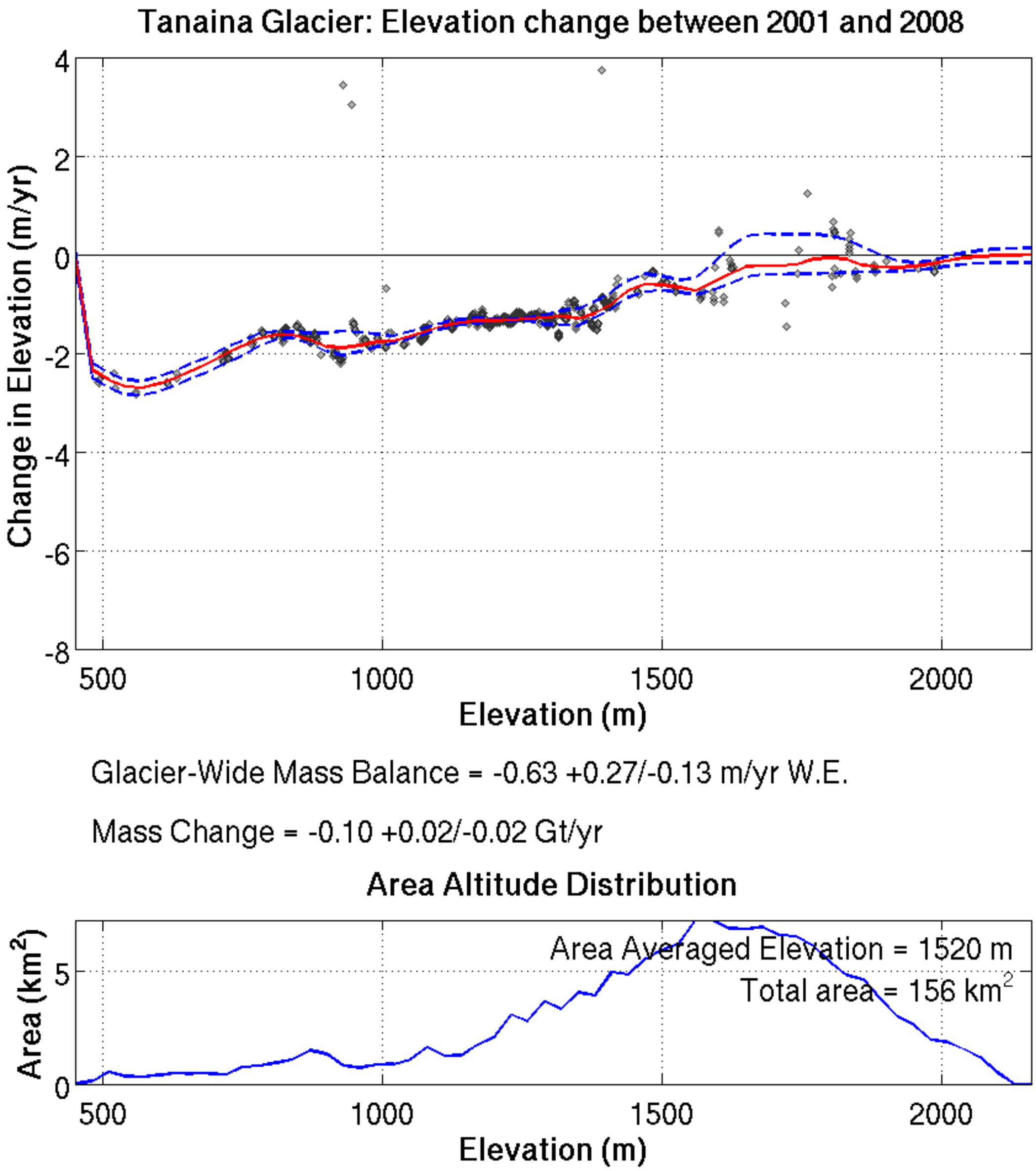


Figure A8. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tanaina Glacier 2001-2008.

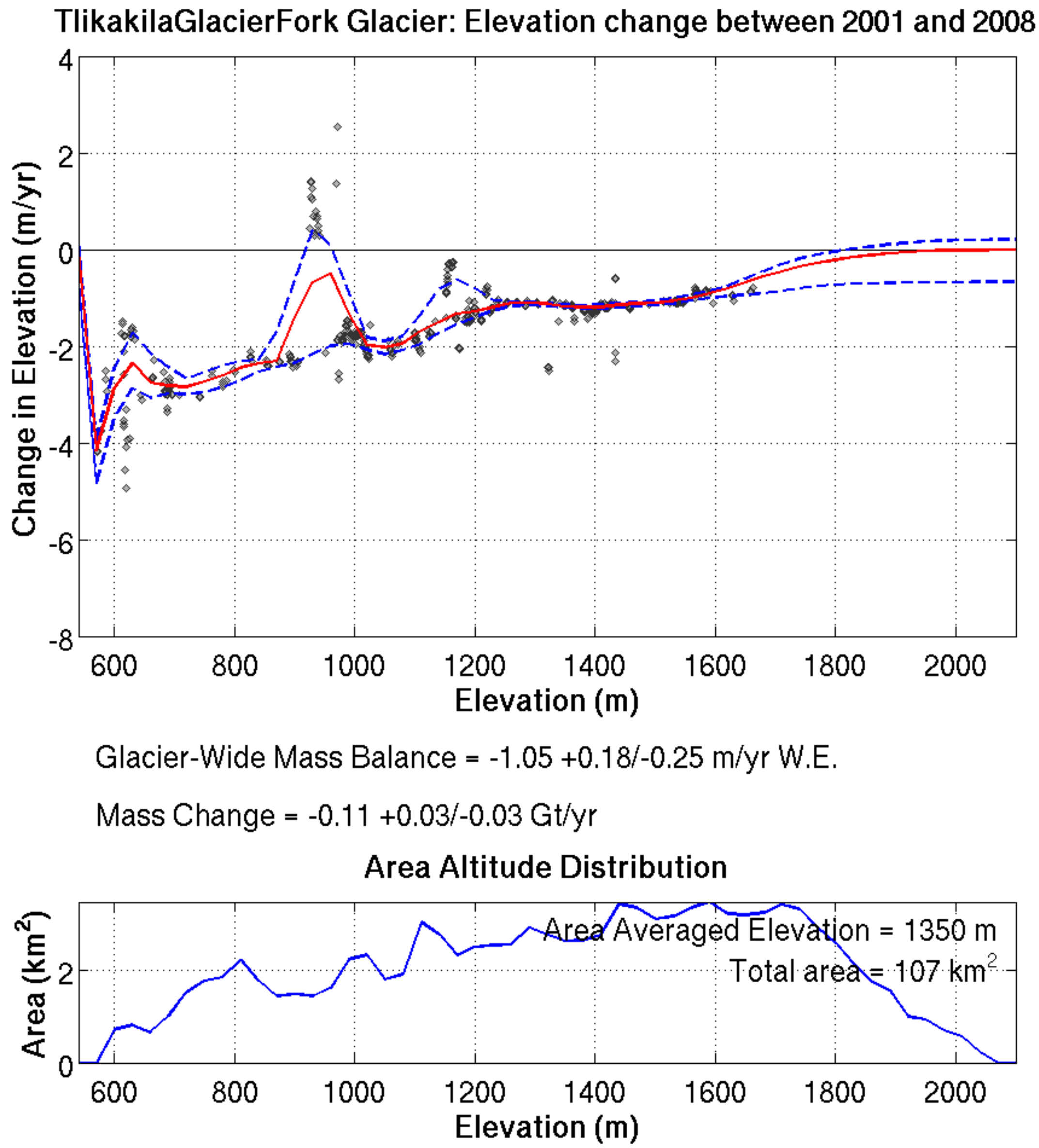


Figure A9. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tlikakila Glacier Fork 2001-2008.

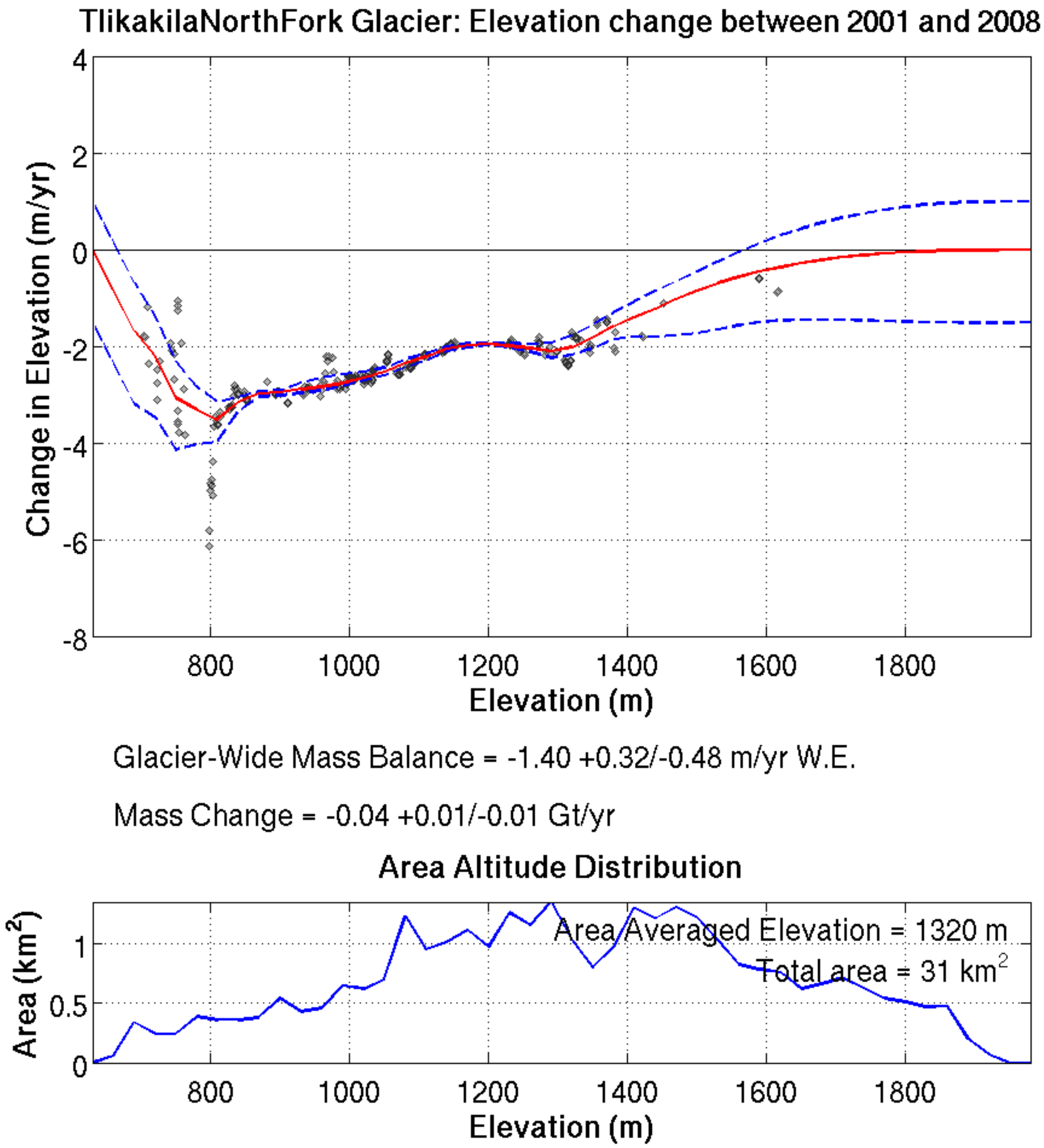


Figure A10. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tlikakila North Fork Glacier 2001-2008.

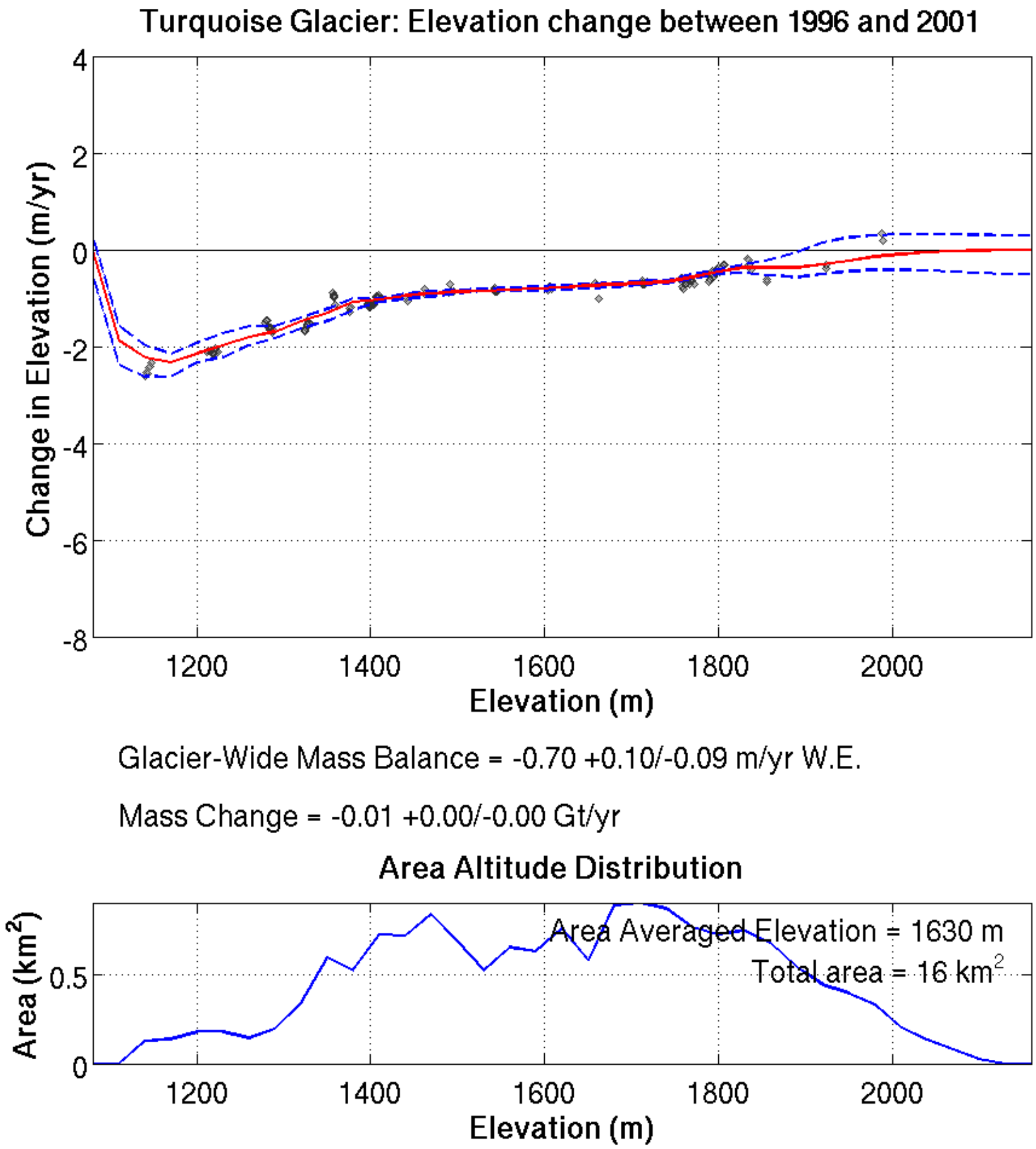


Figure A11. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Turquoise Glacier 1996-2001.

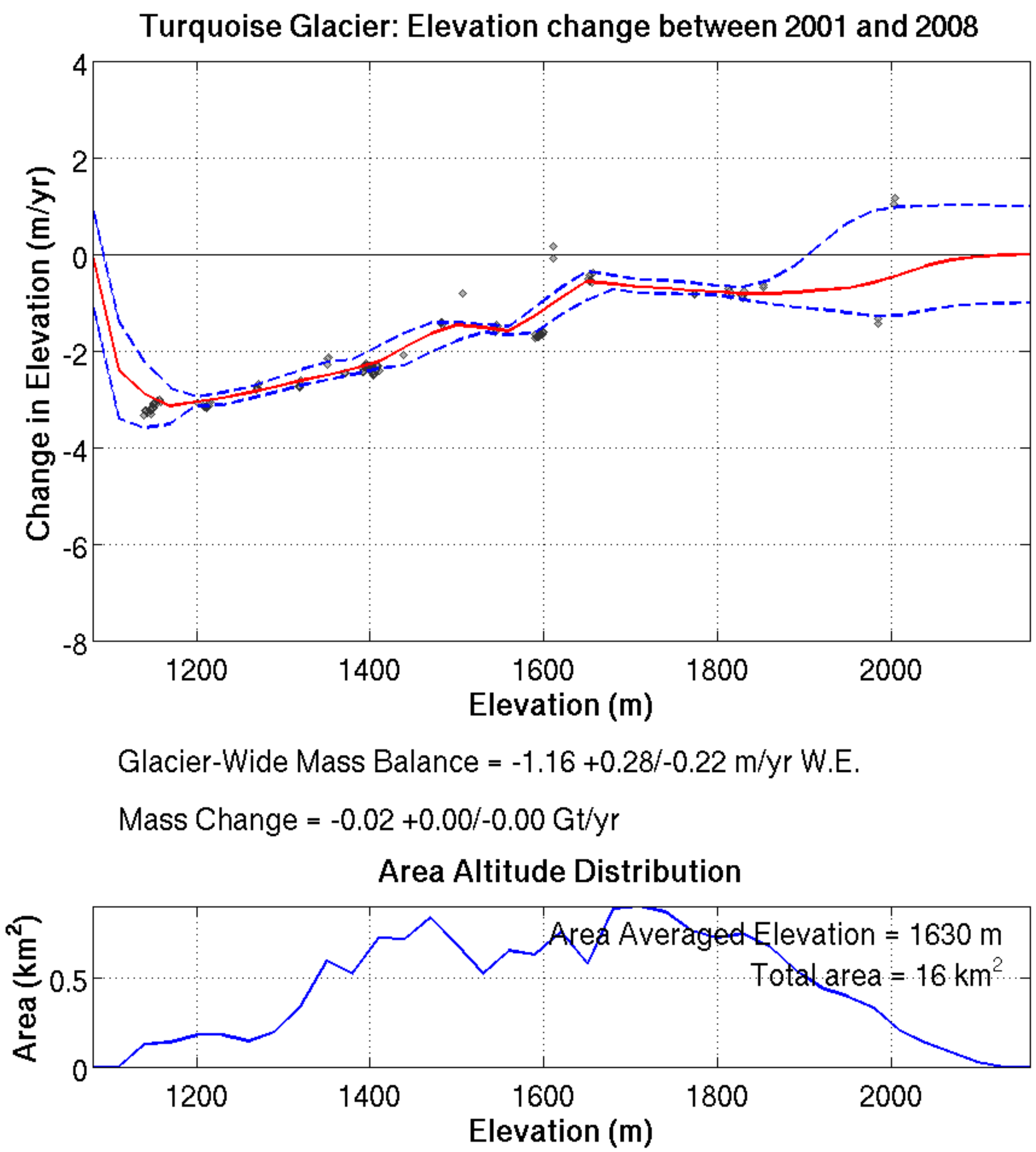


Figure A12. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Turquoise Glacier 2001-2008.

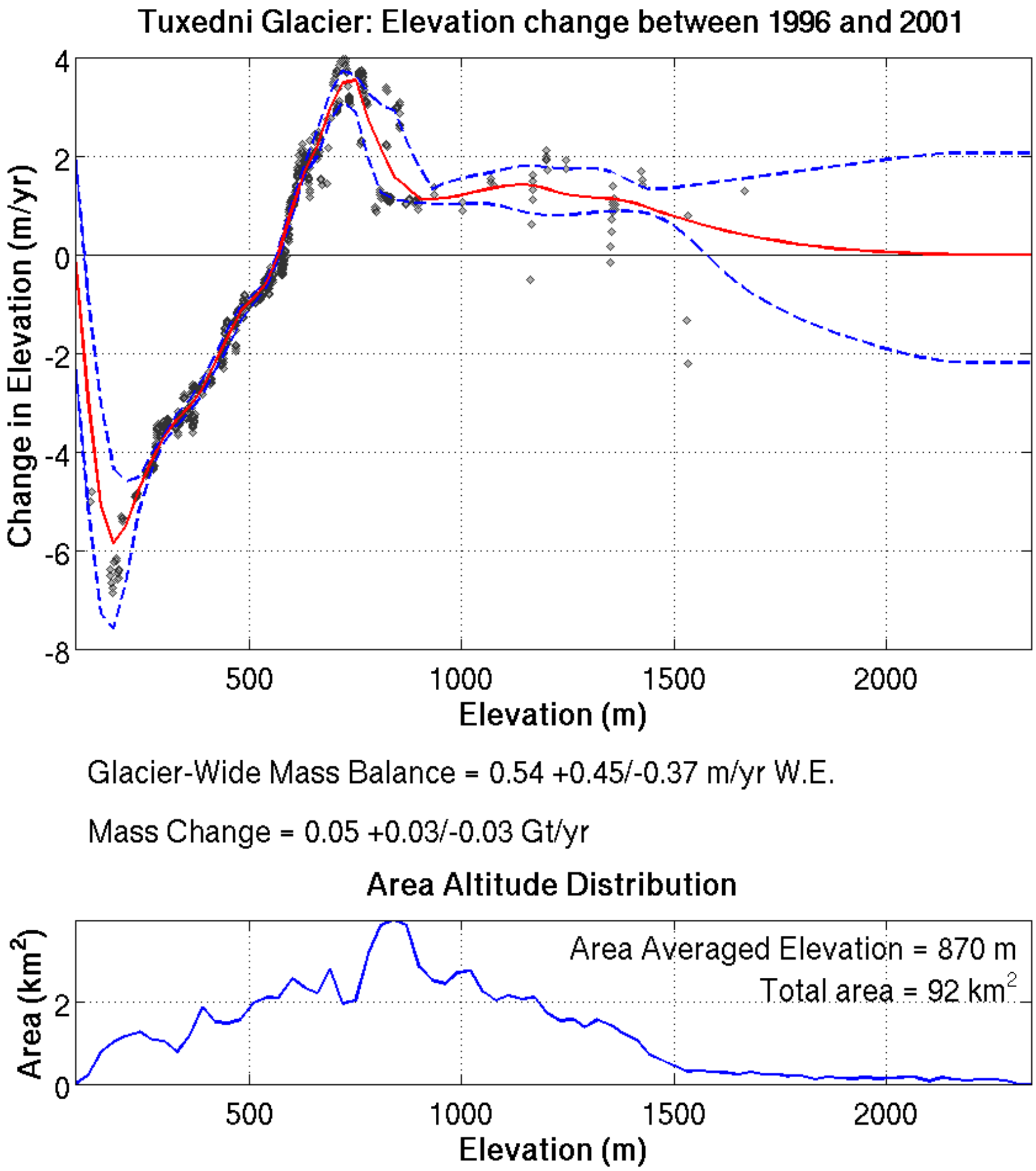


Figure A13. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tuxedni Glacier 1996-2001.

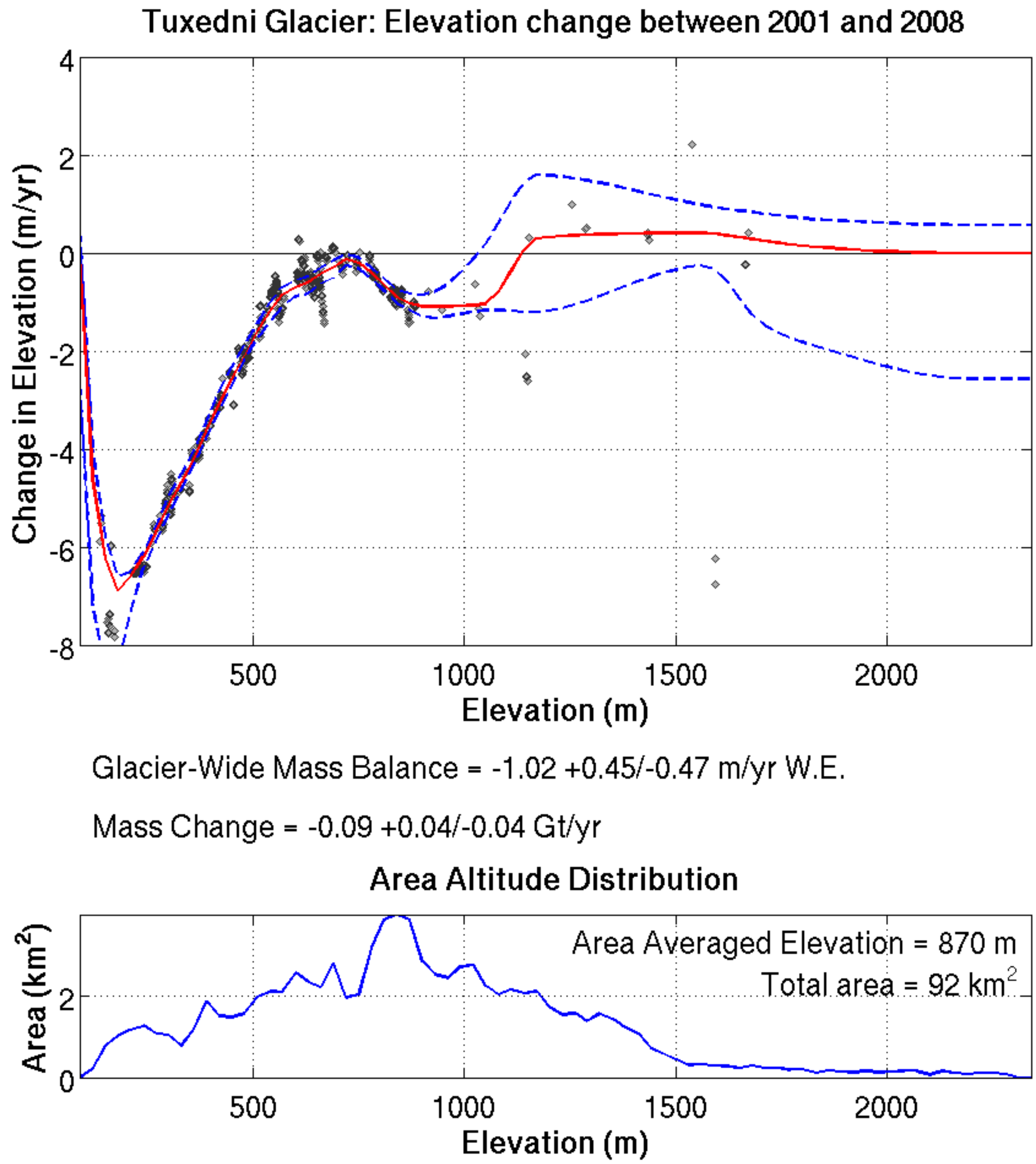


Figure A14. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tuxedni Glacier 2001-2008.

Appendix B: Poster Presented at the SW Alaska Science Symposium November 2-4 2011

Status and Trends of Alaska NPS Glaciers: Workplan and Early Results

Michael G. Loso[1] • Chris Larsen[2] • Anthony Arendt[2] • Nate Murphy[2] • Justin Rich[2]

[1]Alaska Pacific University, Department of Environmental Science, mloso@alaskapacific.edu
[2]University of Alaska Fairbanks, Geophysical Institute

About the Project

➢Glaciers cover about 75,000 km^2 of Alaska's land surface and approximately one-quarter of those glaciers are located within National Park boundaries. To develop a more comprehensive understanding of the glacier resource in Alaskan National Parks and to assess the extent and impacts of recent changes to that resource, NPS recently initiated a collaborative 3-year project with investigators from Alaska Pacific University and University of Alaska Fairbanks. We recently presented our first progress report, available on request. The project will be completed in December 2013.

➢The project has **three major components**:

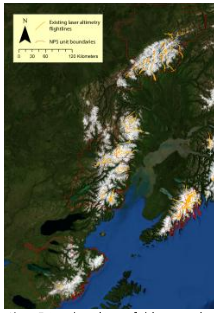
1. map **changes in areal extent** of **all** NPS glaciers in the 1950s (from topographic maps) and the 2000s (from satellite imagery)
2. use existing repeat laser altimetry to estimate **volume changes** in a geographically **diverse subset** of the NPS glaciers
3. more thoroughly characterize historic changes to and landscape-scale impacts of **1-3** "**focus glaciers**" per glaciated park unit

➢Here, we use early results from Southwest Area and other statewide glaciers to document our ongoing methodology and seek feedback on the projected outcomes of the project.

Volume Changes

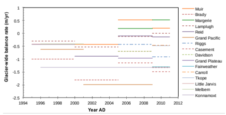
➢Using laser altimetry, we measured 32 distinct intervals of elevation change distributed among sixteen glaciers in **Glacier Bay** between 1995 and 2011. Results from other parks, including SWAN parks (see map below of existing laser altimetry flightlines to be analyzed), will follow.

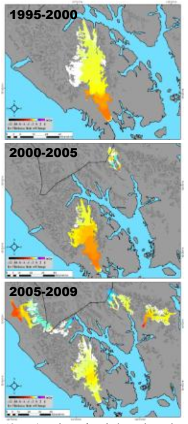
1. Of the measured intervals, all had negative glacier-wide mass balance rates (overall thinning) with five exceptions: positive rates on Muir Glacier 2005-2009 and 2009-2011 and Margerie Glacier 2005-2009, 2009-2011, and one neutral interval (Lamplugh Glacier 2009-2011).
2. The lowest measured balance rate (greatest thinning) was on Grand Pacific Glacier from 2001-2009: ice loss average 1.99 m/yr over the entire glacier surface.



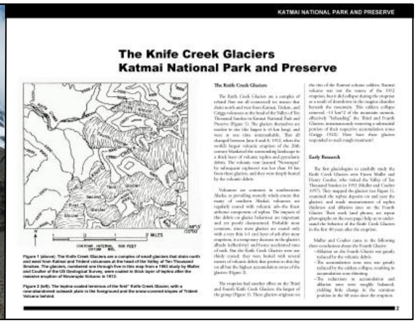
Above: Existing laser altimetry flightlines yet to be analyzed in SWAN parks.

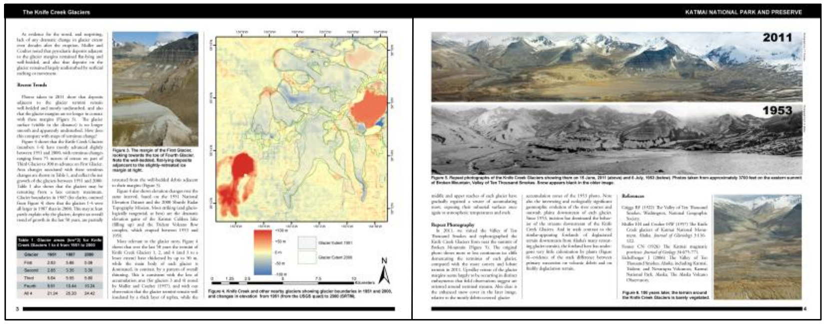
Below: Annual ice thickness change for 16 glaciers in Glacier Bay during multi-year intervals since 1994.





Above: Annual rate of ice thickness change, by elevation, for selected glaciers in Glacier Bay National Park and Preserve in three intervals: 1995 to 2000, 2000 to 2005, and 2005 to 2009.





Focus Glaciers

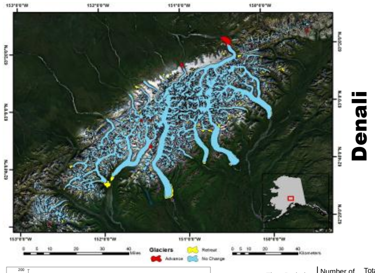
➢**"Focus Glaciers" provide additional information about a small subset** of glaciers in each glaciated park. The goal: demonstrate unique ways in which A) glaciers change in response to climate and other forcings, and B) landscapes respond to glacier change. This portion of the report will include narrative descriptions, photos, maps, figures, and other graphical information.

➢This component of this project focuses on interpretation and synthesis. No new data will be acquired. For each glacier, these materials will ultimately be presented as a "vignette" in the final document. **At right**: a **mock-up** vignette, focused on the **Knife Creek Glaciers**. Note the use of an *Alaska Park Science*-style format. The final project publication will be longer, more focused, and more in-depth than the short articles in that journal, but will be published in a similar graphic format.

➢Criteria for inclusion in the list of focus glaciers includes relative accessibility to visitors, an existing history of documentation including published and unpublished research, and representation of one of the many unique ways that glaciers respond to climatic change.

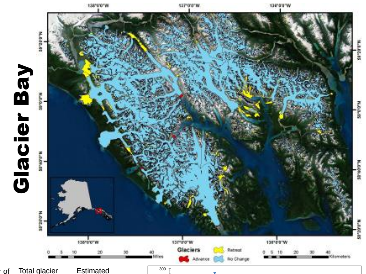
Below: mapped centroids of all selected focus glaciers in the Alaska region. Image courtesy Google Earth.

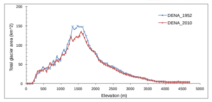
Changes in Areal Extent



➢Here we present results from mapping of all glacier extents in **Glacier Bay NP&P** and **Denali NP&P**. Other parks will follow in similar fashion. Significant early results:

1. Glacier Bay was 53.5% glaciated in 1952, but ice cover diminished 11% by 2010, to become 48.4% glaciated (6427 km^2).
2. Denali was 16.9% glaciated in 1952, but ice cover diminished 8% by 2010, to become 15.5% glaciated (3817 km^2).
3. The vast majority of glaciers in both parks have shrunk considerably, mainly by terminus retreat, in that time.
4. A few glacier termini advanced in Glacier Bay since 1952. All these advances are by tidewater or recently-tidewater glaciers in retracted positions that may indicate a resumption of normal tidewater glacier expansion.
5. Only two significant glacier expansions occurred in Denali since 1952. Both were surge-type glaciers: Muldrow and Peters Glaciers.



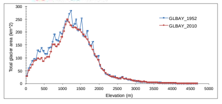


Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1952)	1103	4149	1051
Modern (2010)	754	3817	996
Absolute Change	-249	-332	-55
Percent Change	-23%	-8%	-5%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using exponent/coefficient values of 0.2055/1.375 from Radic and Hock (2010).

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1952)	1120	7106	1729
Modern (2010)	1283	6427	1507
Absolute Change	163	-779	-222
Percent Change	15%	-11%	-13%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using exponent/coefficient values of 0.2055/1.375 from Radic and Hock (2010).



Appendix C: Code Definition and Screenshot of the Mapping Database

Database Fields

ID: glacier identification code
Name: common name of glacier, if known
Code: Standard code describing glacier type
Date: Year of image/data acquisition
Latitude: Latitude of glacier centroid in decimal degrees
Longitude: Longitude of glacier centroid in decimal degrees
Area: glacier area (km^2)
Elev_Min: minimum (terminus) elevation (m)
Elev_Max: maximum (headwaters) elevation (m)
Median: area-weighted median elevation (m)
Mean: area-weighted mean elevation (m)
B0: glacier area in 0 to 50 m elevation bin (m^2)
B50: glacier area in 50 to 100 m elevation bin (m^2)
B100: glacier area in 100 to 150 m elevation bin (m^2)
Etc: bins continue to highest glacier elevation at 50 m increments

ID	Name	Code	Date	Latitude	Longitude	Area	Elev_Min	Elev_Max	Median	Mean	B0	B50	B100
G154453W58311N		0	20090711	58.3112	-154.4535	0.874	927	1309	1020	1032	0	0	0
G155061W58366N		0	20090824	58.3661	-155.0618	1.349	912	2250	1296	1385	0	0	0
G153847W58655N		0	20090824	58.6556	-153.8473	0.507	669	1079	945	923	0	0	0
G153825W58693N		0	20090824	58.6939	-153.8257	0.669	658	1025	816	824	0	0	0
G153809W58715N		0	20090824	58.7160	-153.8094	0.587	917	1354	1029	1049	0	0	0
G153824W58724N		0	20090824	58.7246	-153.8242	1.558	612	1312	1011	1009	0	0	0
G153835W58765N		0	20090824	58.7653	-153.8360	0.126	1063	1210	1146	1147	0	0	0
G155416W58164N		0	20090904	58.1641	-155.4160	3.335	877	1803	1229	1250	0	0	0
G155287W58176N		0	20090904	58.1767	-155.2875	1.437	1242	1892	1431	1458	0	0	0
G155271W58170N		0	20090904	58.1703	-155.2720	0.961	1056	1520	1268	1279	0	0	0
G155222W58192N		0	20090904	58.1924	-155.2223	3.759	790	2173	1472	1505	0	0	0
G155306W58195N		0	20090904	58.1956	-155.3062	13.424	663	2157	1257	1331	0	0	0
G155388W58146N		0	20090904	58.1462	-155.3885	6.915	942	1852	1396	1400	0	0	0
G154994W58239N		0	20080725	58.2397	-154.9944	4.026	667	1870	1335	1348	0	0	0
G154950W58243N		0	20090711	58.2433	-154.9502	1.073	961	1738	1328	1319	0	0	0
G154538W58455N		0	20090824	58.4555	-154.5389	0.52	1004	1432	1264	1251	0	0	0
G154538W58441N		0	20090824	58.4413	-154.5389	2.773	1020	1751	1304	1314	0	0	0
G154376W58488N		0	20090824	58.4886	-154.3765	14.538	441	1976	902	998	0	0	0
G154267W58467N		0	20090824	58.4675	-154.2672	3.534	631	1742	1112	1111	0	0	0
G154535W58394N		0	20090619	58.3944	-154.5360	40.401	367	2265	1072	1079	0	0	0
G154591W58345N	Serpent Tong	0	20090619	58.3454	-154.5918	27.173	583	2156	1073	1125	0	0	0

NPS 953/117460, October 2012

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov